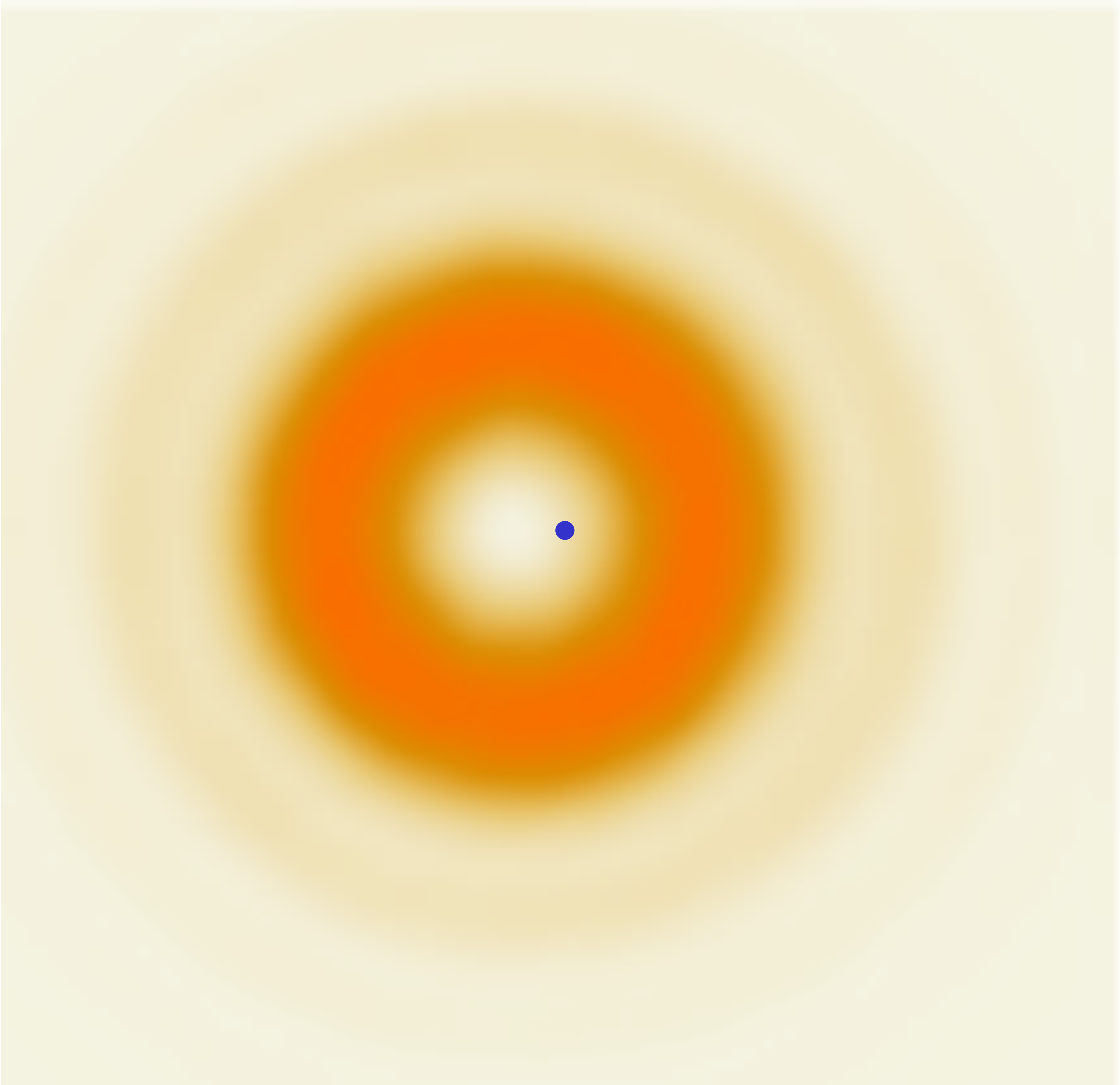
How to twist, turn, and kick ions using structured light



Slides ↓↓

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Ciudad de Buenos Aires - Argentina

Paraty 2025 - RJ - Brasil

Structure of this course

1) Structured light basics

2) Structured light and atoms

3) Structured light and optical forces

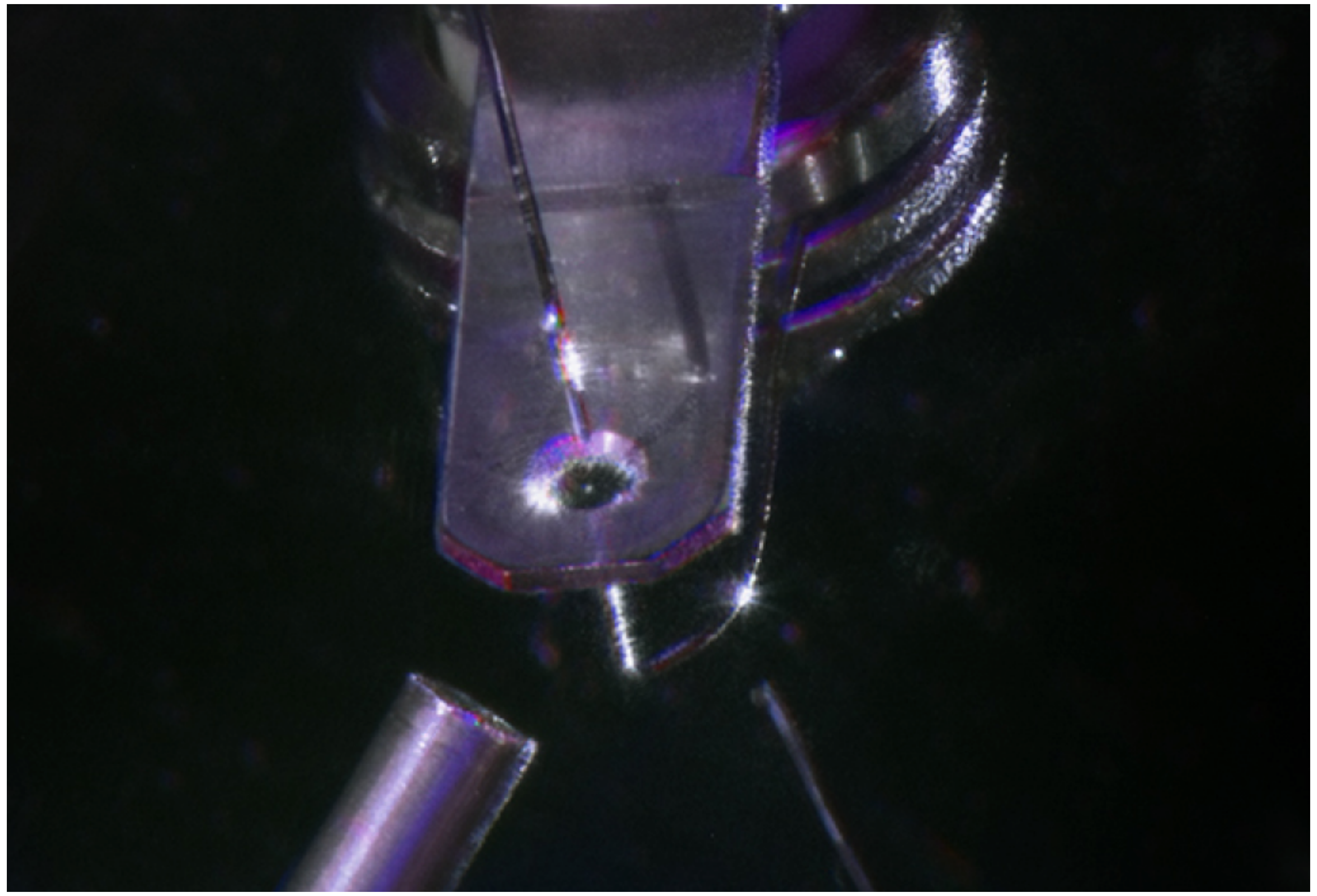
Day Two

Part x

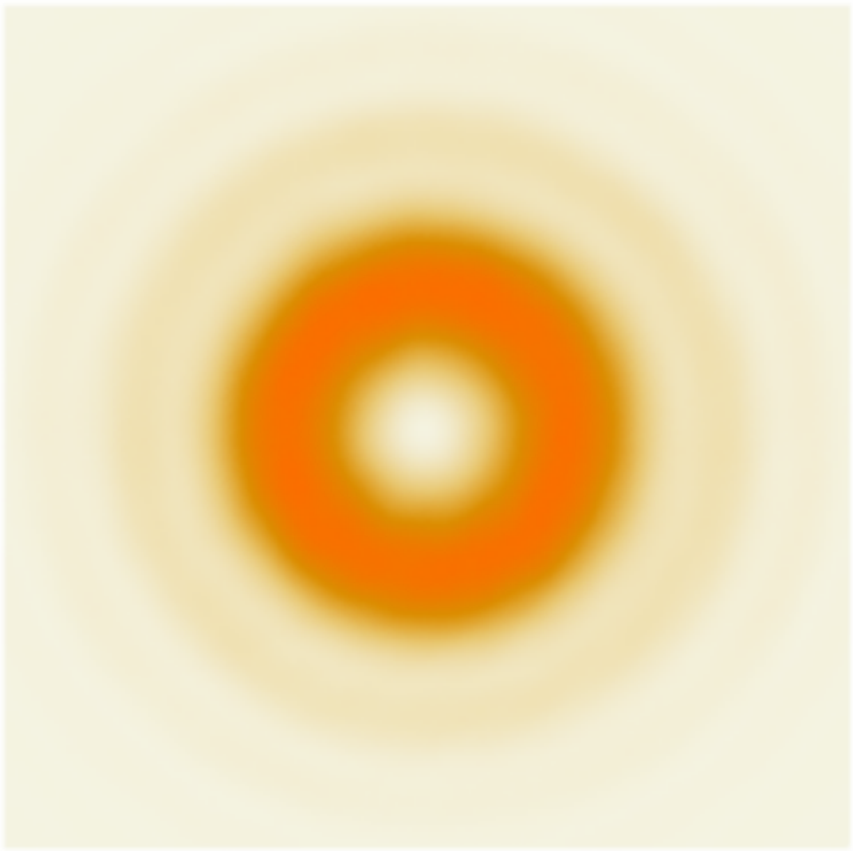
Review Day 1

Dancing in the dark - the Sao Paulo anecdote, ca. 2008

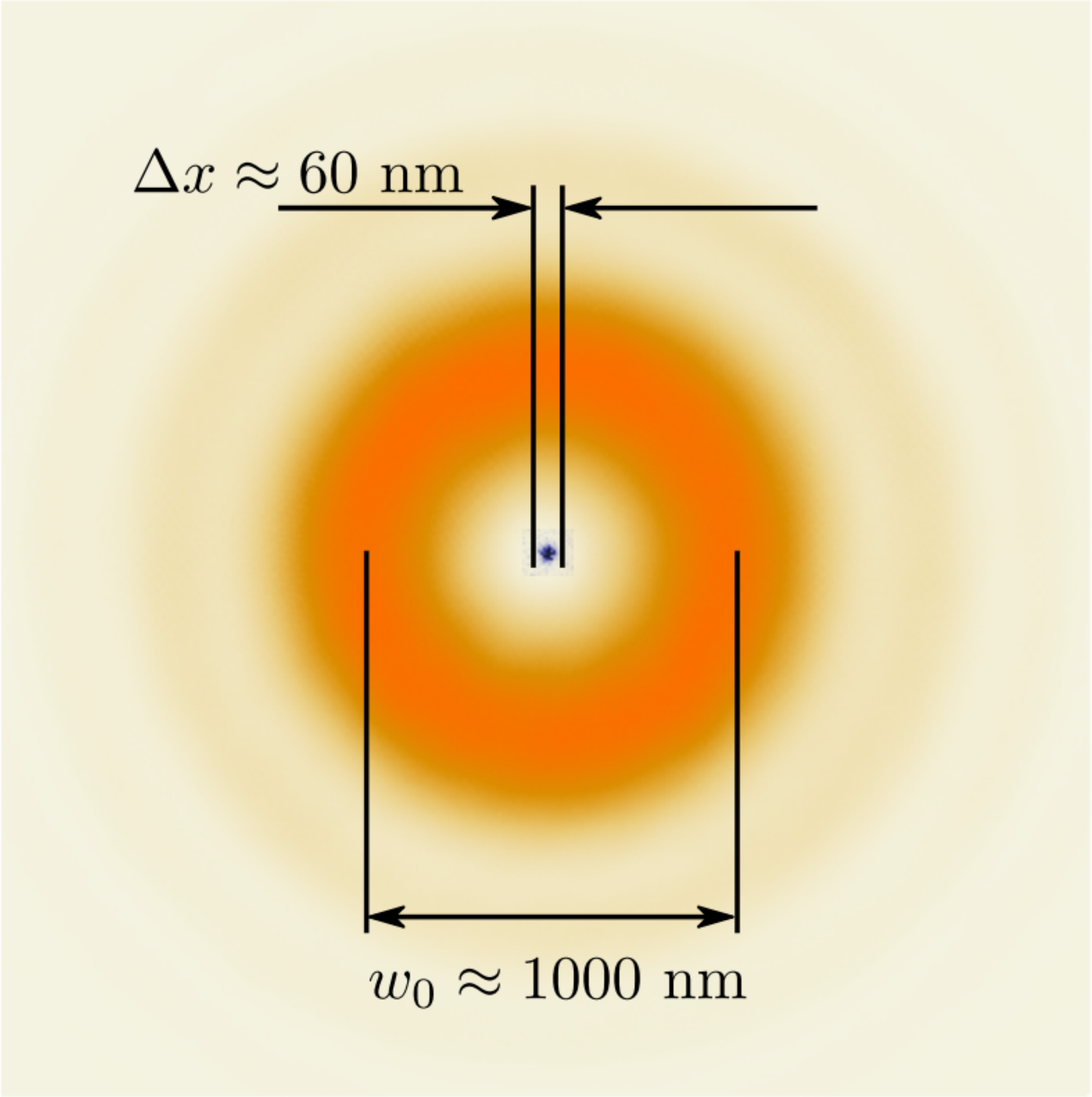
an ion trap



a hollow beam



ion in a beam



Twisted Light

$$A = A_{lp}(\rho, \phi, z)\vec{\epsilon} e^{ikz} e^{-i\omega t}$$

$$\mathbf{A}_{lp} = \mathbf{A_0} \; \frac{w_0}{w(z)} \exp\left(\frac{-\rho^2}{w(z)} + \frac{ik\rho^2}{2R(z)} + i\Phi_g(z) \right)$$

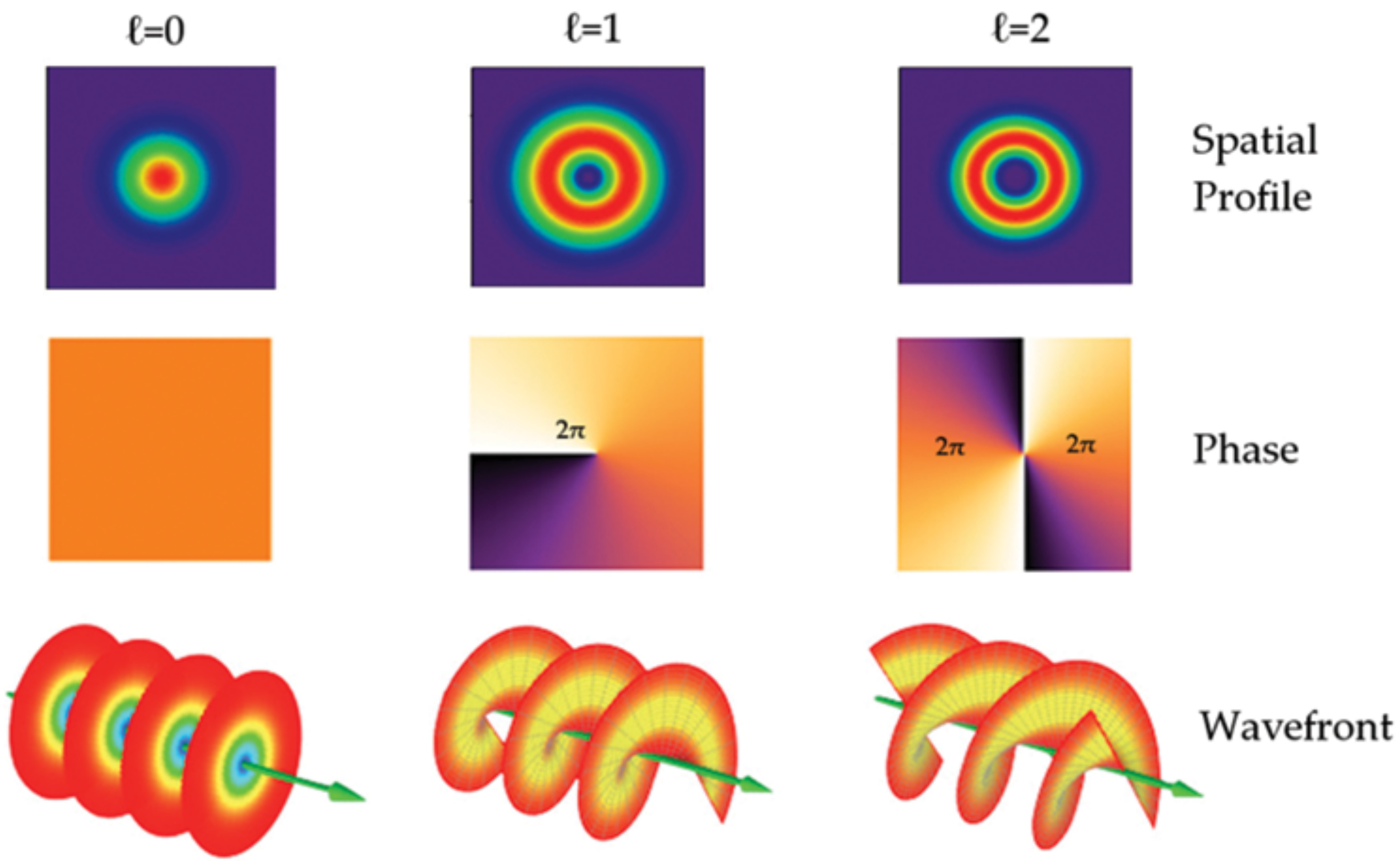
$$\sqrt{\frac{2p!}{\pi(|l|+p)!}} \left(\frac{\sqrt{2}\rho}{w(z)} \right)^{|l|} \mathcal{L}_p^{|l|} \left(\frac{2\rho^2}{w^2(z)} \right) \exp(il\phi)$$

$l = 0$ $l = 1$ $l = 2$

Light Angular Momentum

$$M_z = \frac{l}{\omega} |u|^2 + \frac{\sigma_z r}{2\omega} \frac{\partial |u|^2}{\partial r} \; .$$

Twisted Light - spiraling beams



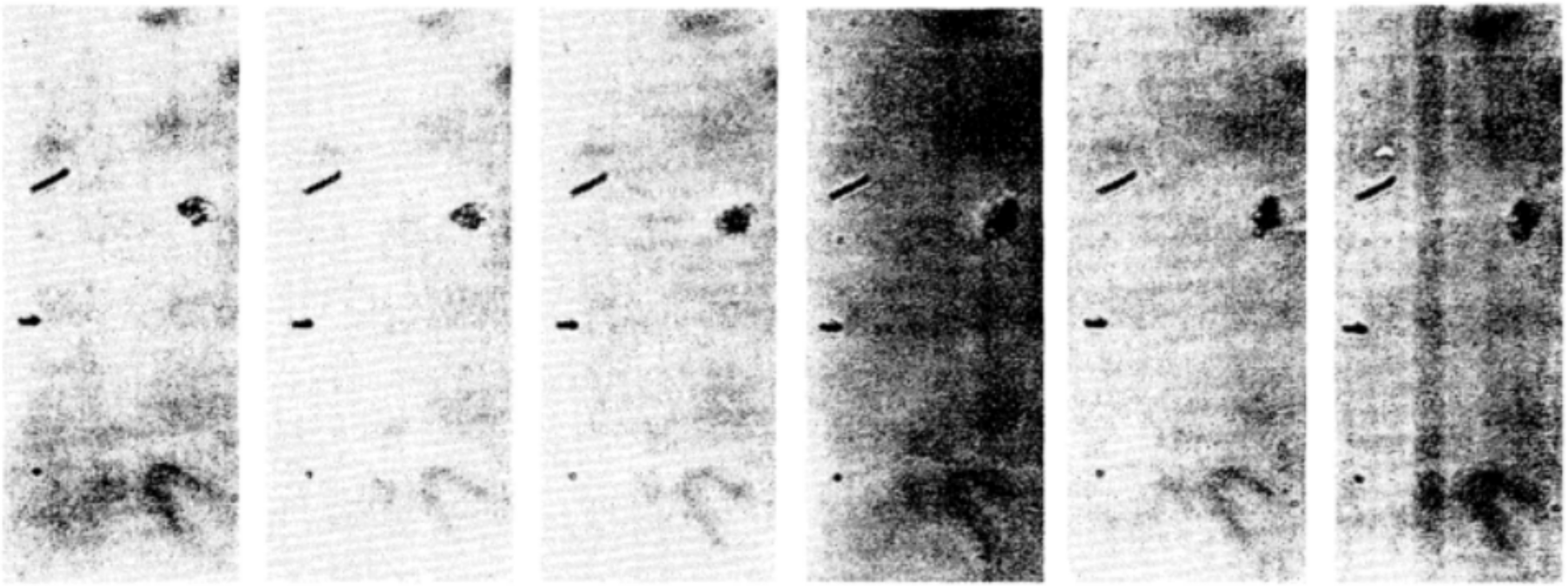
Orbital Angular Momentu - first experiment

VOLUME 75, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 1995

pg. 826

Direct Observation of Transfer of Angular Momentum to Absorptive Particles from a Laser Beam with a Phase Singularity

H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop
Department of Physics, The University of Queensland, Brisbane, Queensland, Australia Q4072



Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum	✓ Fraunhofer	✓ Radiation Pressure	✓ Refraction
Spin Angular Momentum	✓ Hanle & Bät	✓ Beth	✓ Optical Activity
Orbital Angular Momentum		✓ Rubenstein Dunlop	

Day Two

Part 1

Quadrupole Interactions

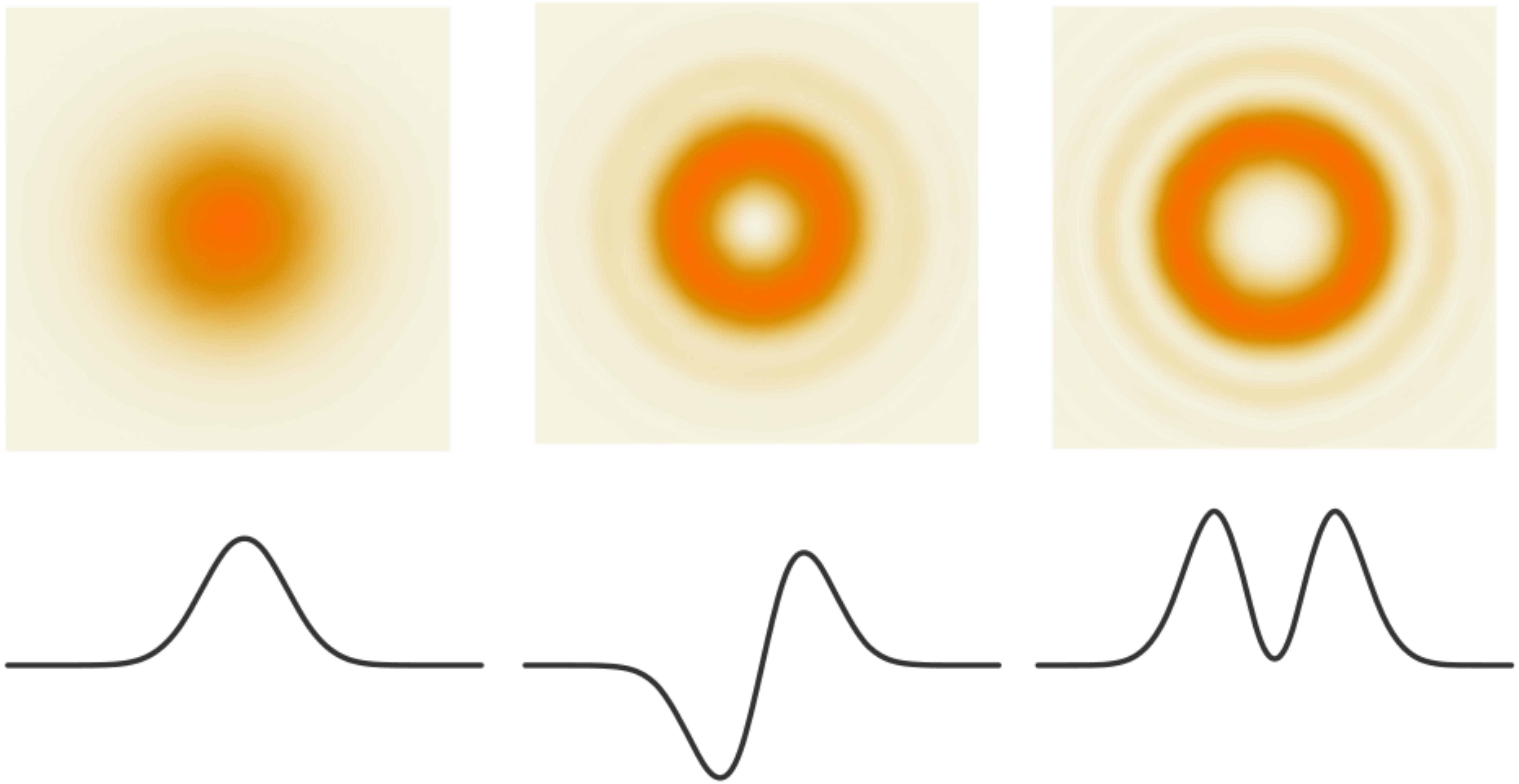
Dancing in the dark Structured light beams - Laguere- Gauss type.

Equation of the LG beams $A = A_{lp}(\rho, \phi, z)\vec{\epsilon} e^{ikz} e^{-i\omega t}$

$$\mathbf{A}_{lp} = \mathbf{A_0}\ \frac{w_0}{w(z)} \exp\left(\frac{-\rho^2}{w(z)} + \frac{ik\rho^2}{2R(z)} + i\Phi_g(z)\right) \sqrt{\frac{2p!}{\pi(|l|+p)!}} \left(\frac{\sqrt{2}\rho}{w(z)}\right)^{|l|} \mathcal{L}_p^{|l|}\left(\frac{2\rho^2}{w^2(z)}\right) \exp(il\phi)$$

$|A_{pl}(x,y)|^2$
Intensity

$A_{pl}(x)$
Field



Dancing in the dark Ferdinand's insight -> Go Quadrupole!

Recap: matrix elements & selection rules

Fermi's Golden Rule $\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|H_{int}|i\rangle\right|^2 \rho$

Light-Matter Interaction $H_{int} \propto A\cdot p + p\cdot A$

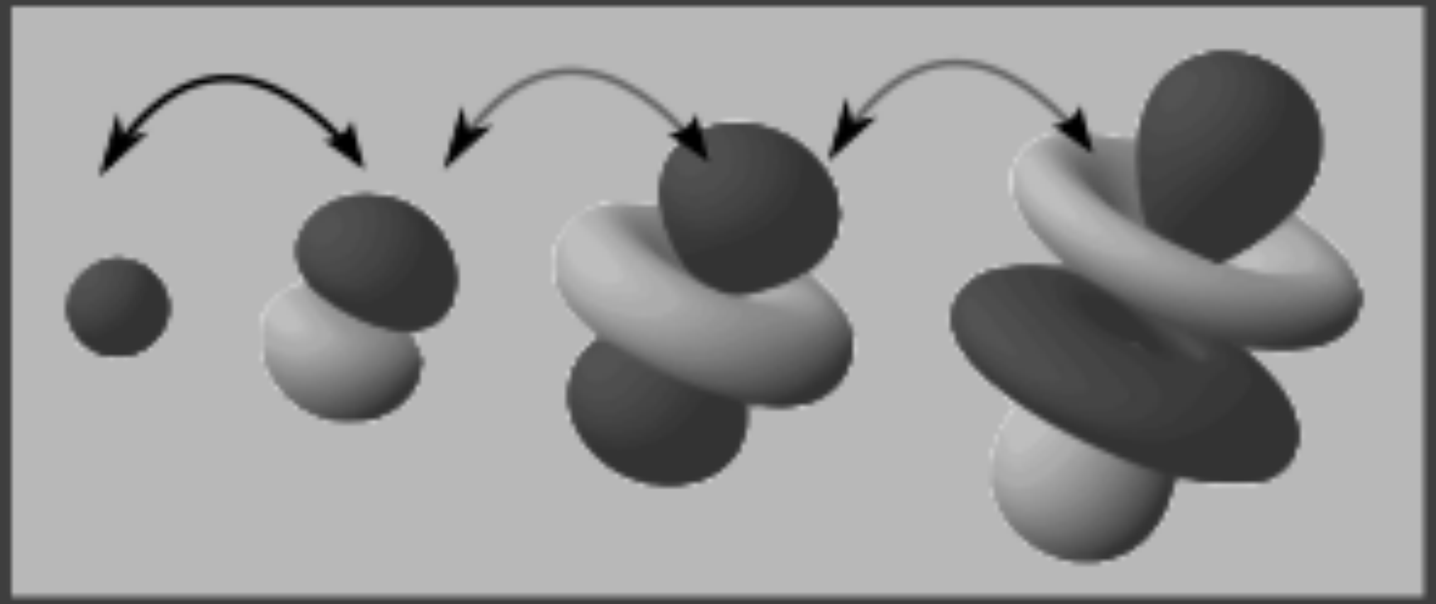
$$\langle f|\mathcal{H}_\mathcal{I}|i\rangle \propto \langle f|\mathbf{A}\cdot\mathbf{p}+\mathbf{p}\cdot\mathbf{A}|i\rangle \propto \omega_{fi}\langle f|\mathbf{r}\cdot\mathbf{A}|i\rangle$$

Electric Dipole

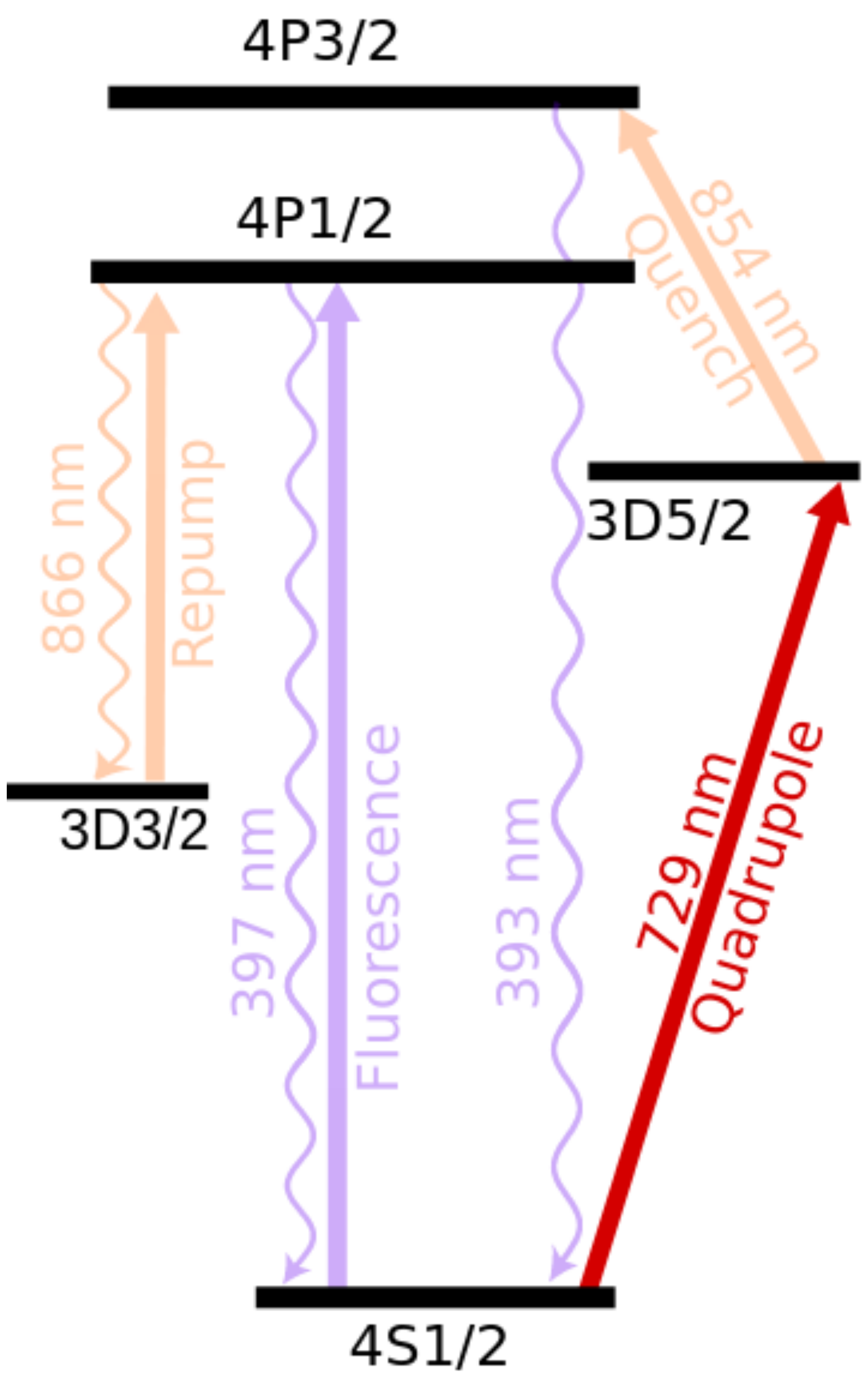
oscilating electric field

$$\mathbf{A} \approx \mathbf{A}_0\vec{\epsilon}e^{-i\omega t}$$

$|i\rangle, |f\rangle \qquad \Delta l = 1$



Calcium ion energy levels



Dancing in the dark

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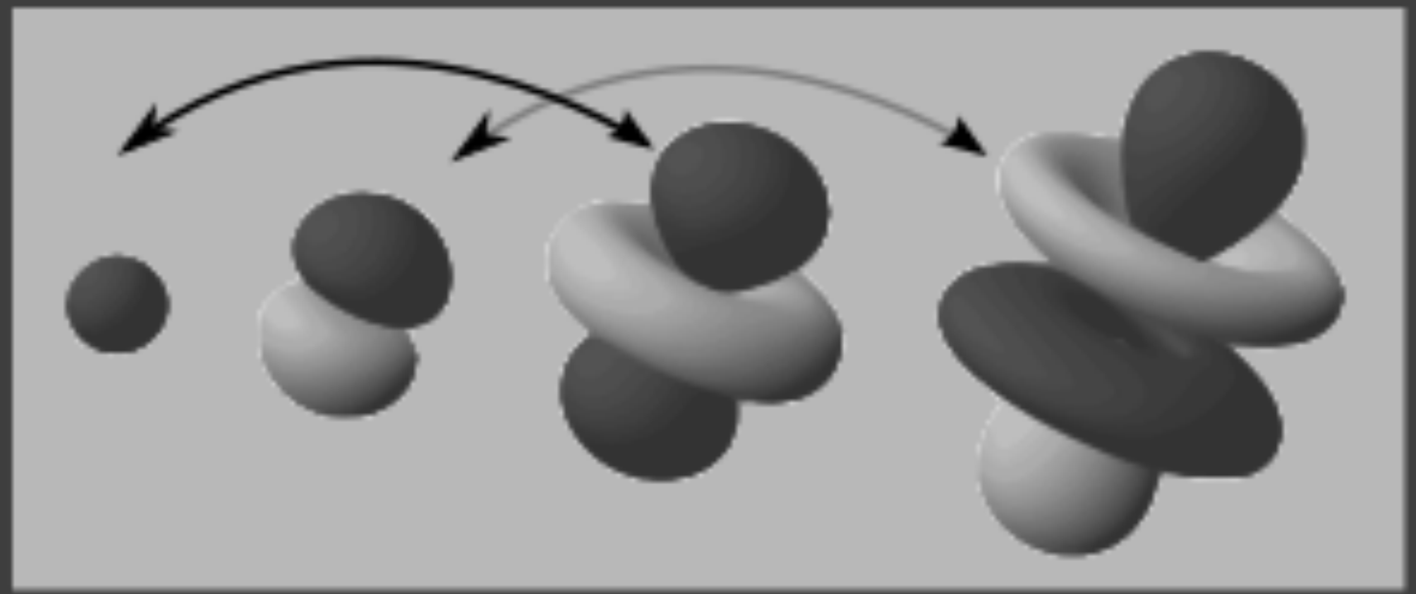
Electric Quadrupole

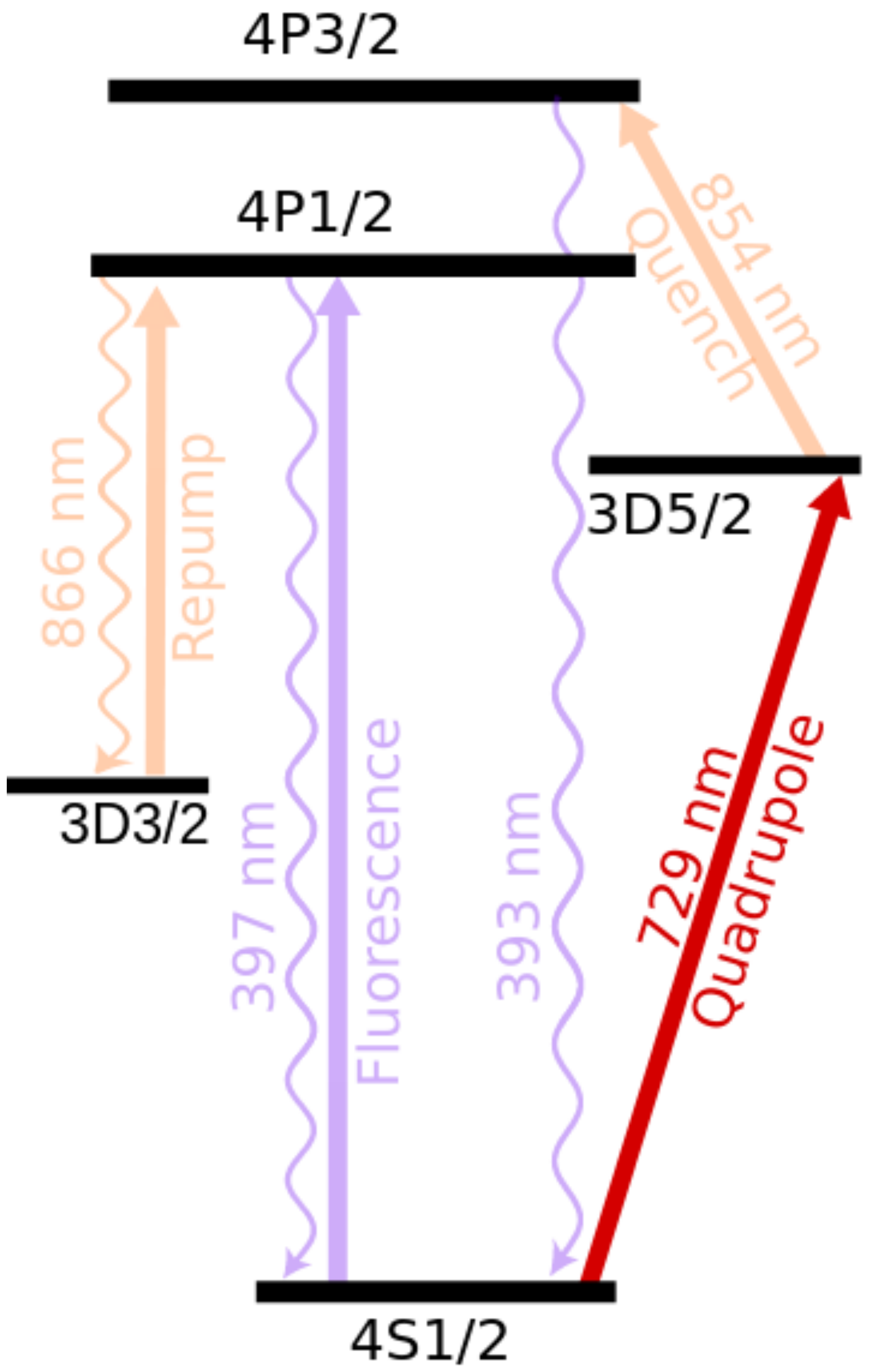
oscilating gradient - it's a wave!

$$\mathbf{A} \approx \mathbf{A}_0 ikz\vec{\epsilon}e^{-i\omega t}$$

$|i\rangle, |f\rangle \quad \Delta l = 2$



Calcium ion energy levels



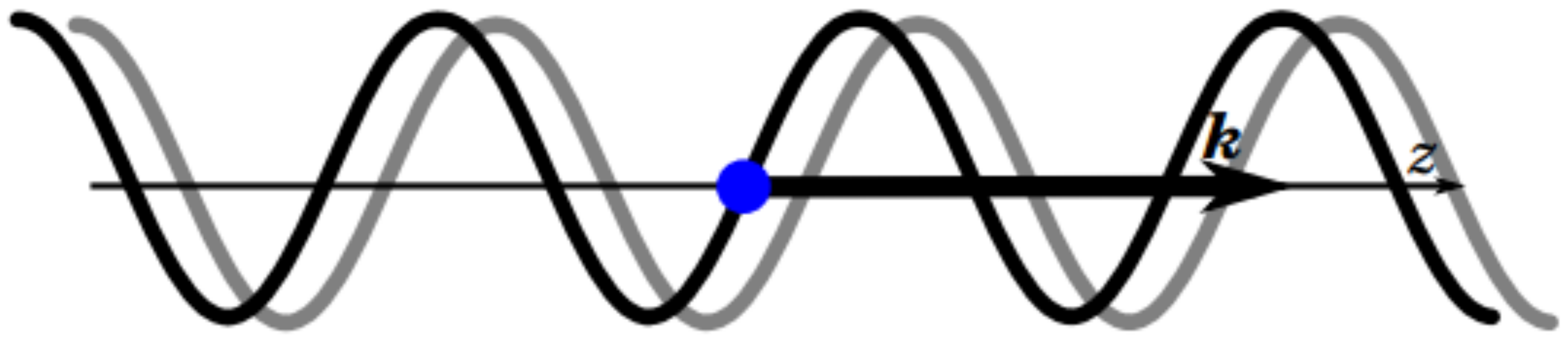
Dancing in the dark Where do the gradients come from?

Travelling Wave

$$\mathbf{A} = \mathbf{A}_0 e^{i(kz-\omega t)}$$

Field Amplitude and
Longitudinal Gradient

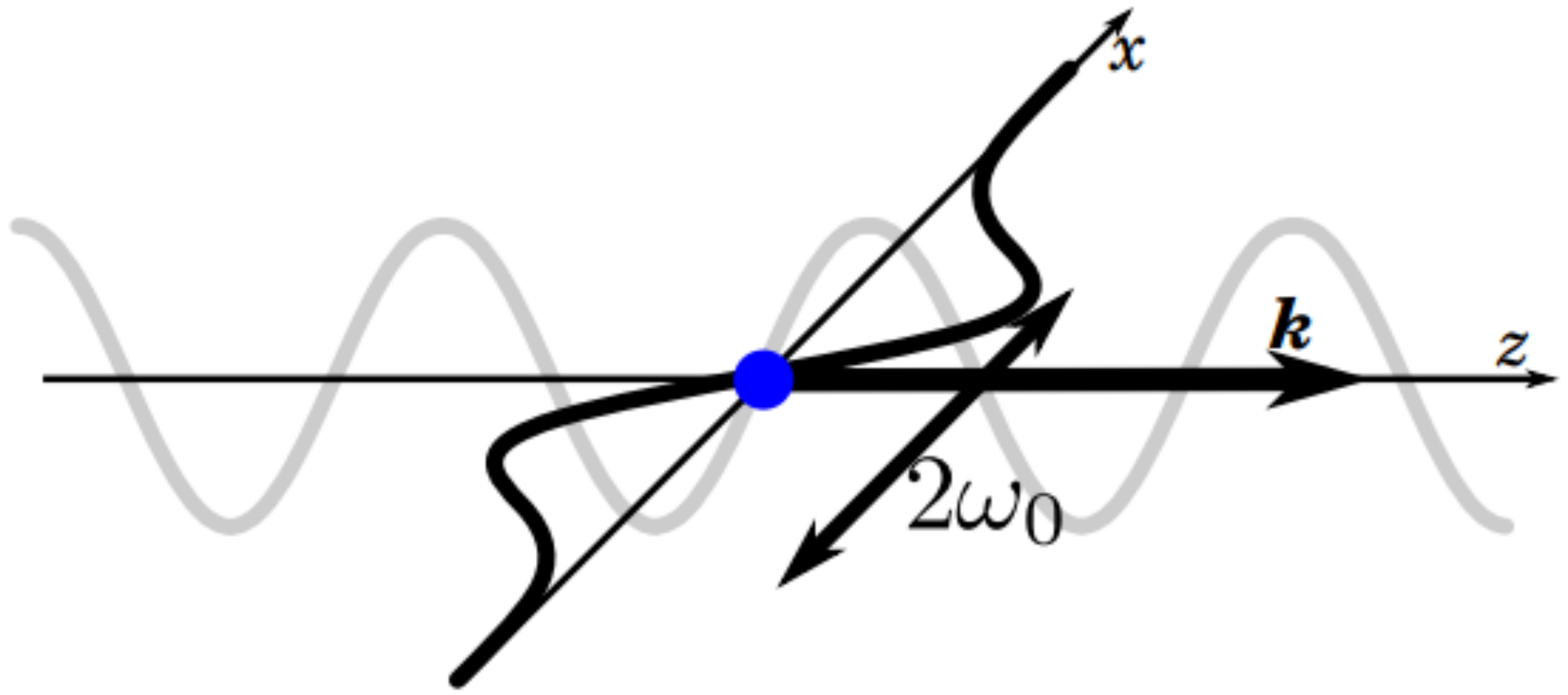
$$\mathbf{A} \approx \mathbf{A}_0(1 + ikz)e^{-i\omega t}$$



Vortex Beam

Transerse Field Gradient
with no Amplitude

$$\mathbf{A}_{10} \approx \mathbf{A_0}\frac{\sqrt{2}\rho}{w_0}e^{i\phi}\, e^{-i\omega t}$$

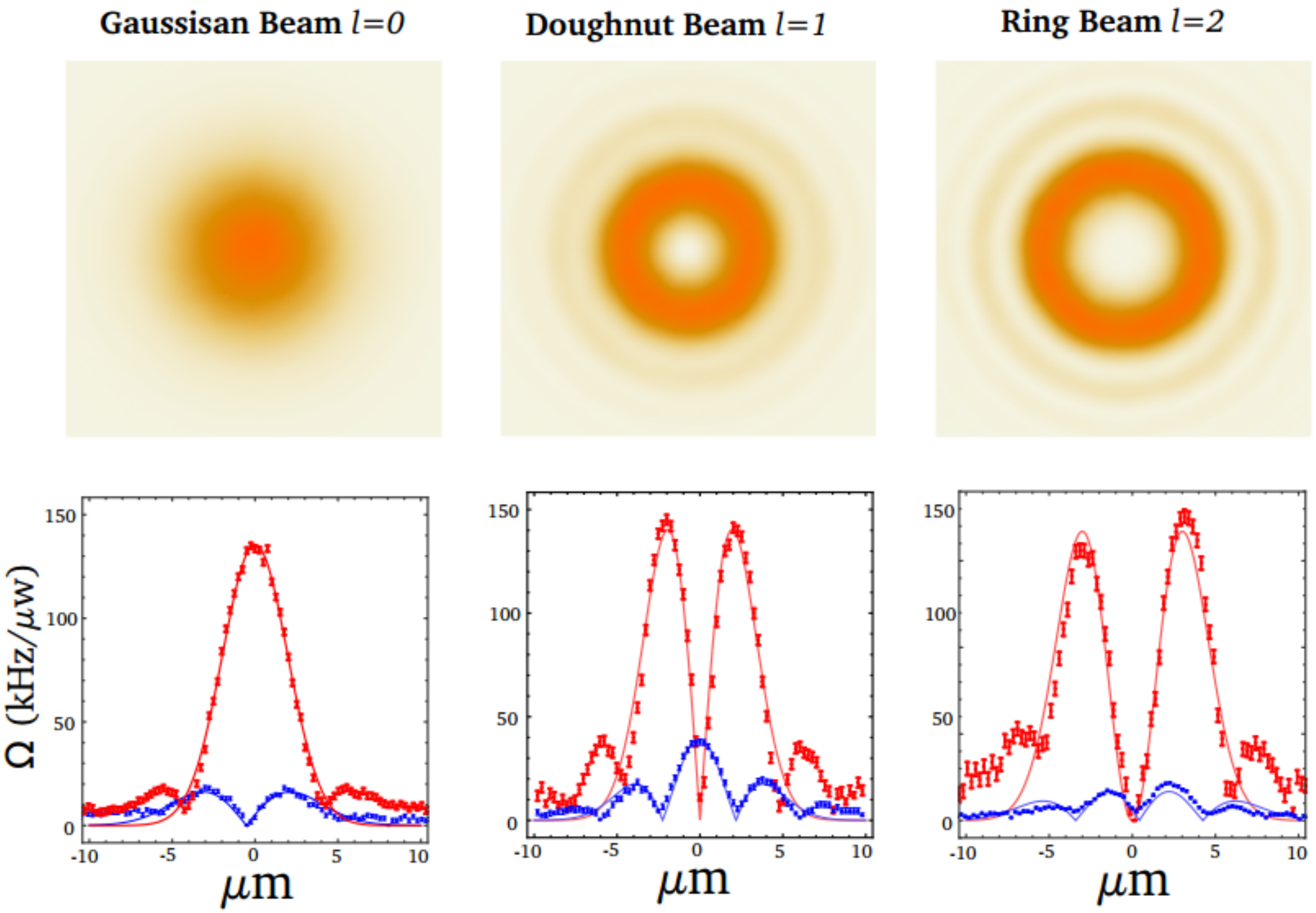


Beam Intensity Profiles
(measured with CCD
before focusing on the ion)

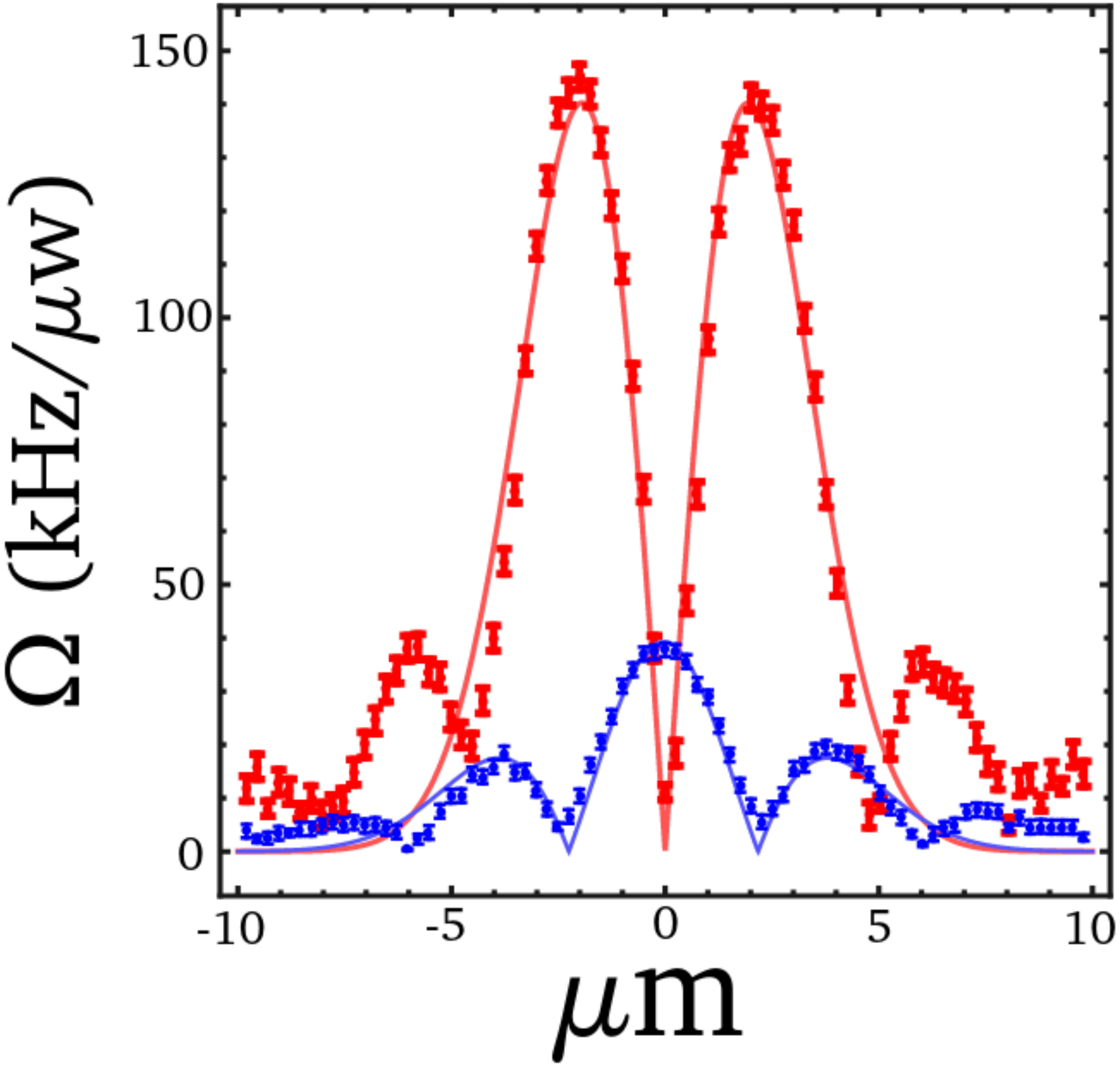
Quadrupole Excitation
as a function of the
position of the ion
in the beam

Longitudinal Gradient
proportional to sqrt(intensity)

Transverse Gradient



Nature communications 7, 12998 (2016)



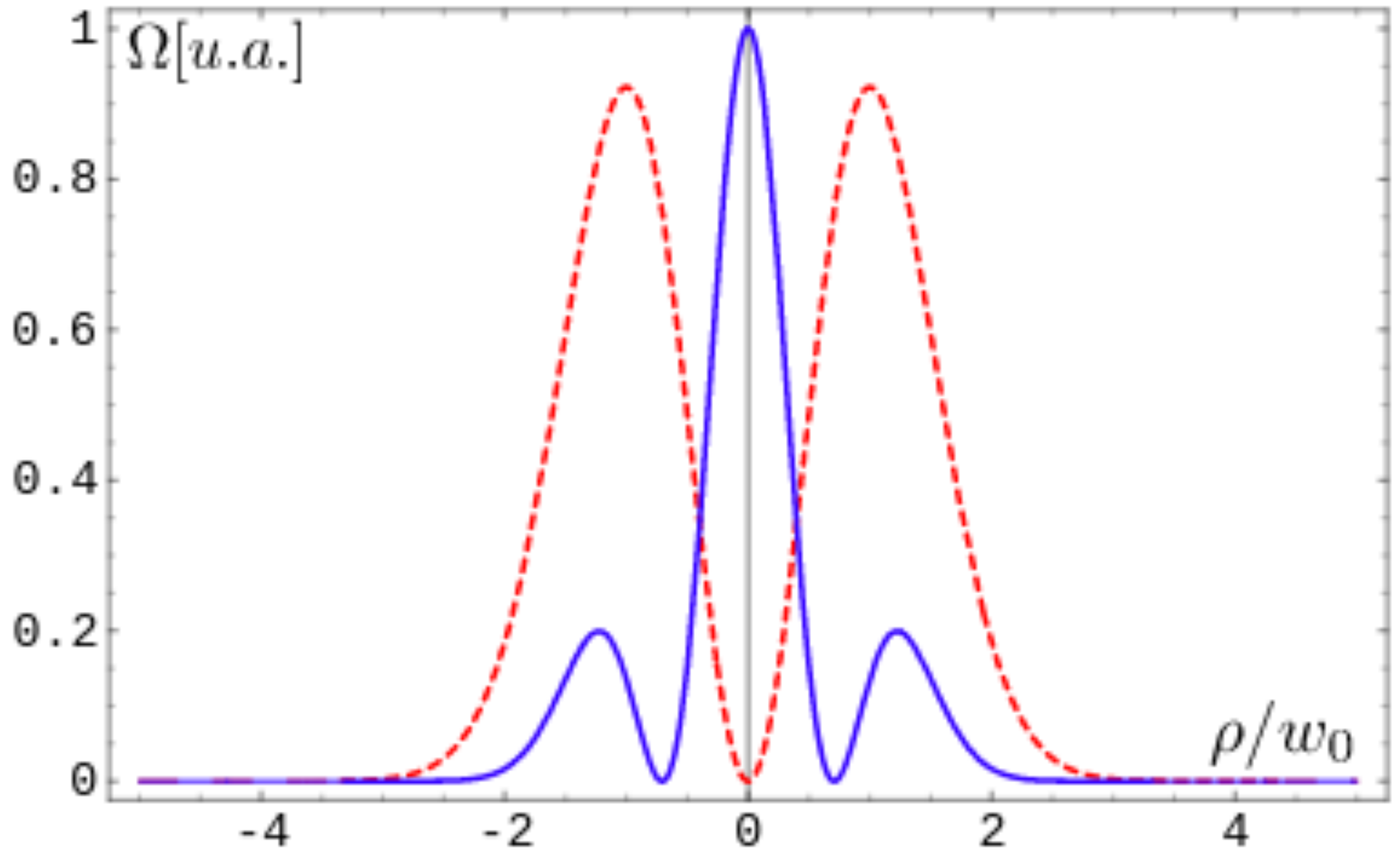
Longitudinal Gradient

- proportional to sqrt(intensity) -

Transverse Gradient

prediction Schmiegelow & Schmidt-Kaler

Eur. Phys. J. D **66**: 157 (2012)



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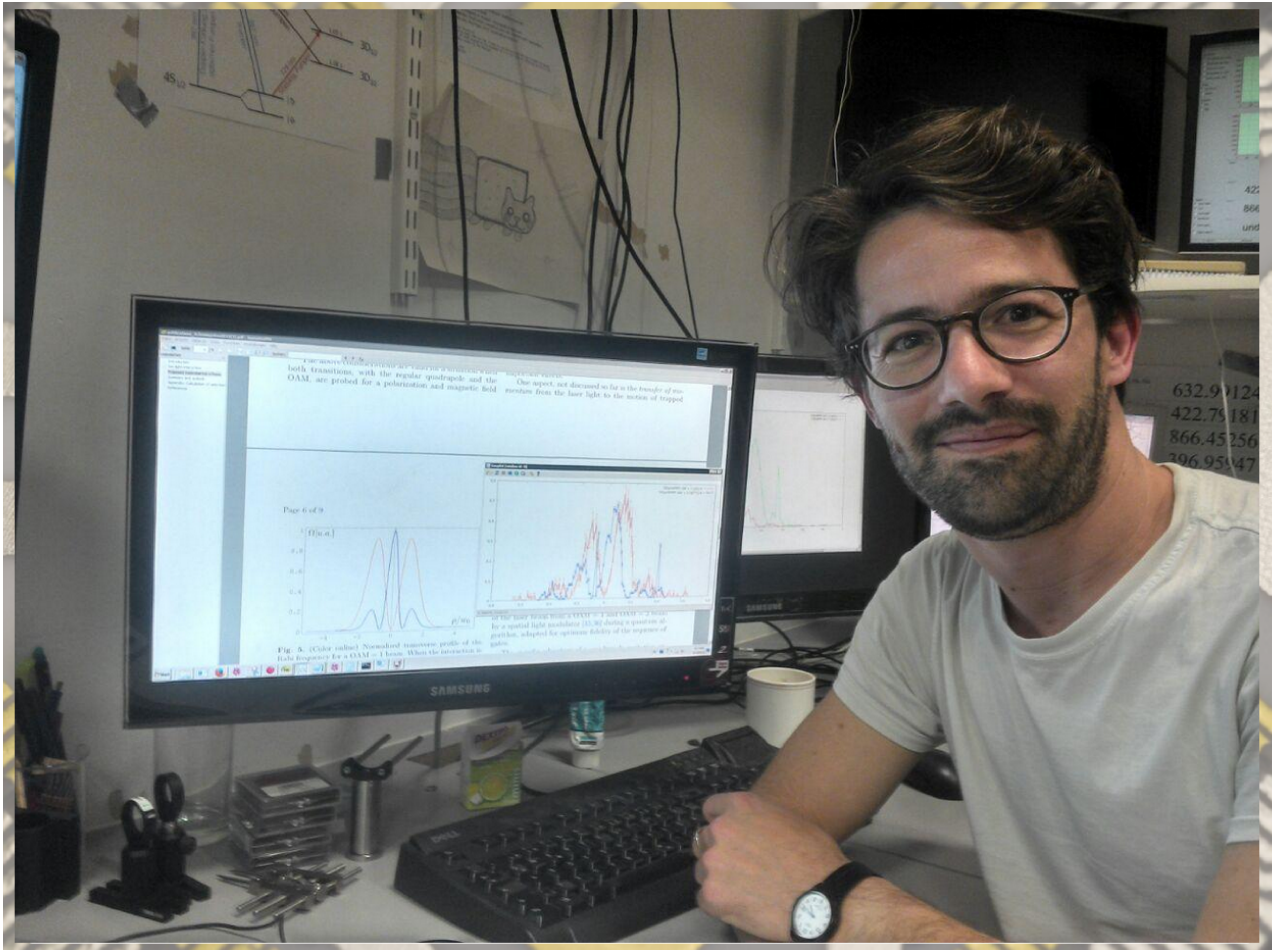
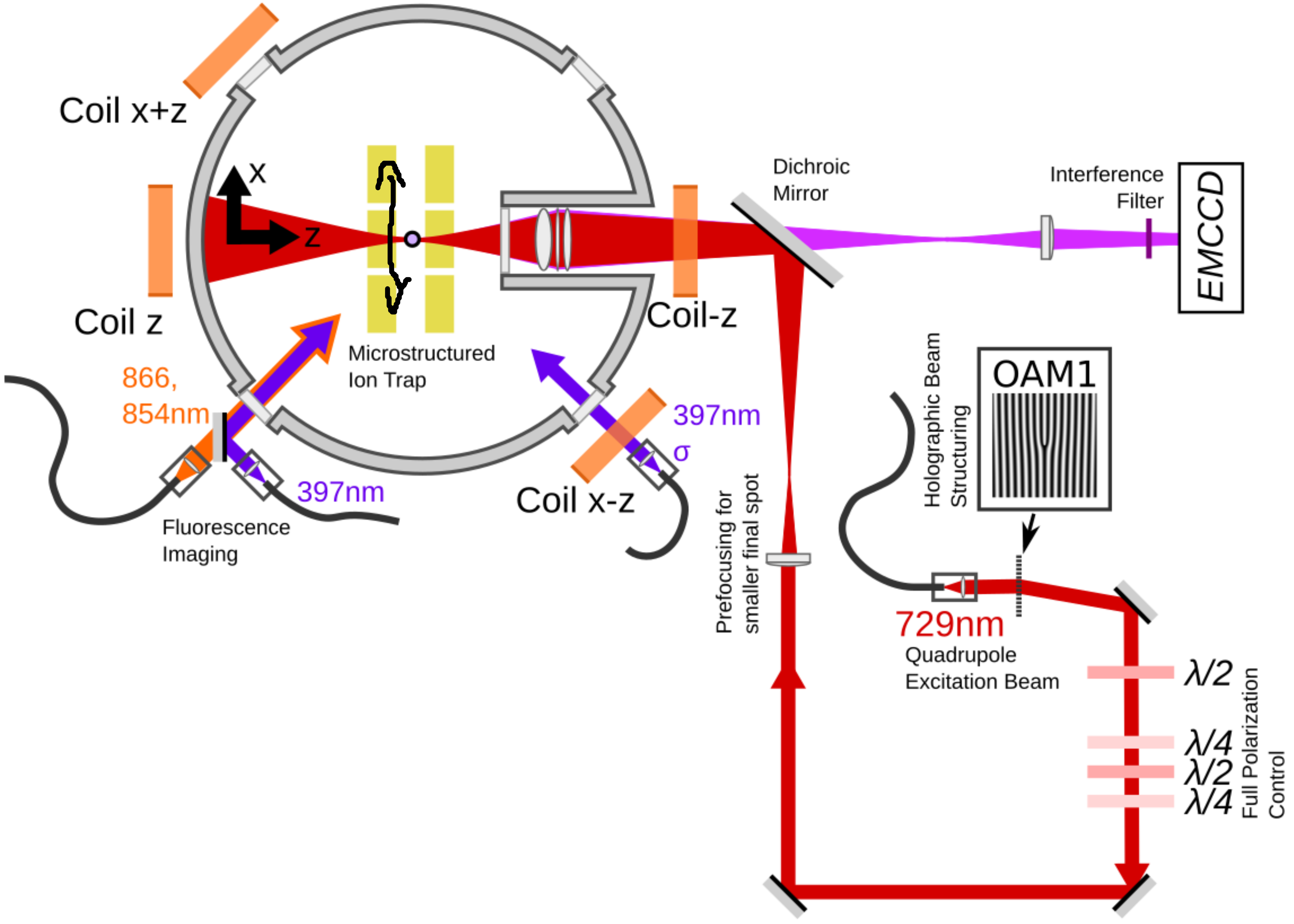


Things i've learned
- shut up and calculate
- leave ideas rest
- it's the optics, stupid

Experimental setup



Day Two

Part 2

Ion Trapping

How to trap ions

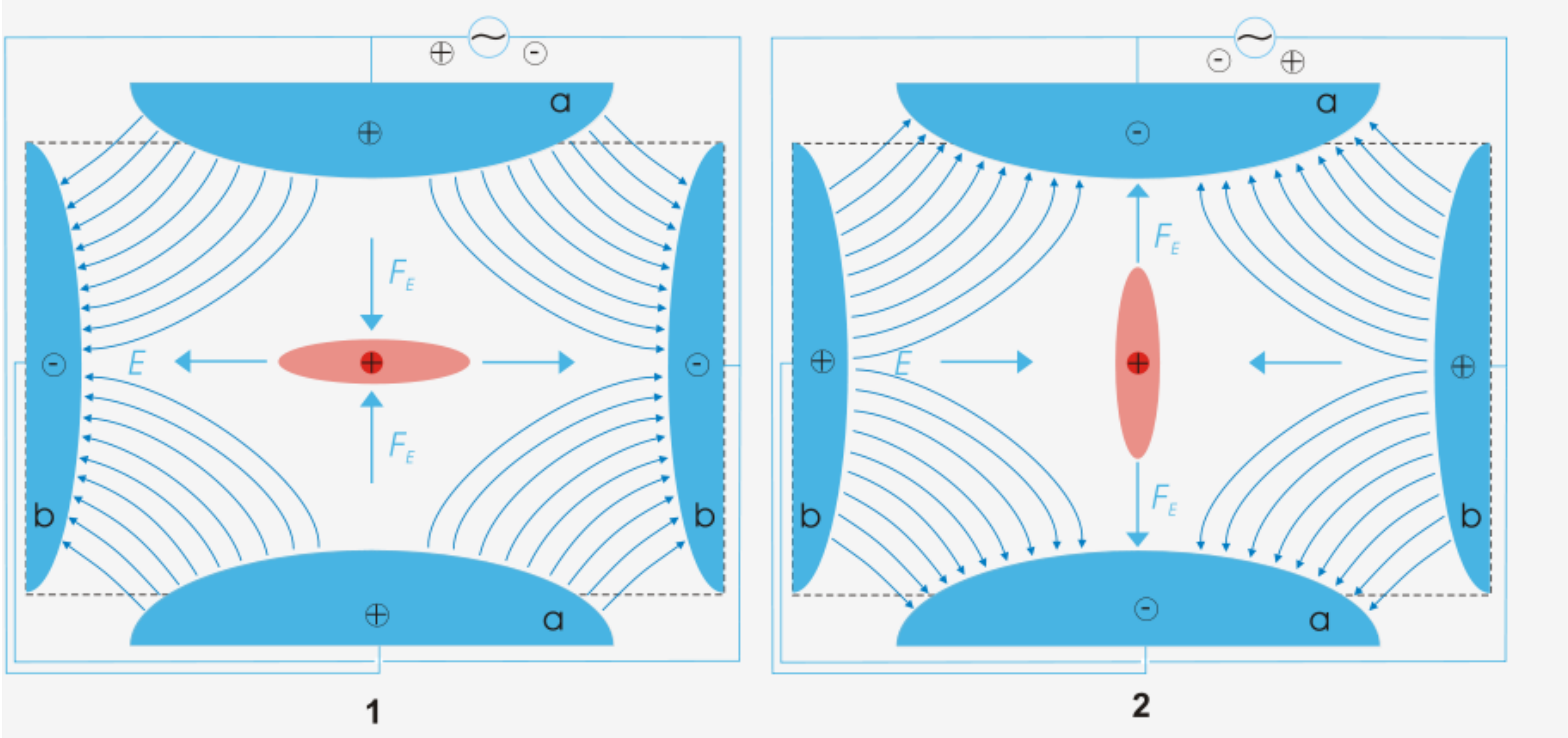
A trap
A vacuum chamber
Atoms
An ionization method
An observation method

trap diagrams and Earnshaw's theorem

How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

Paul trap working mechanism - oscillating potential



How to trap ions

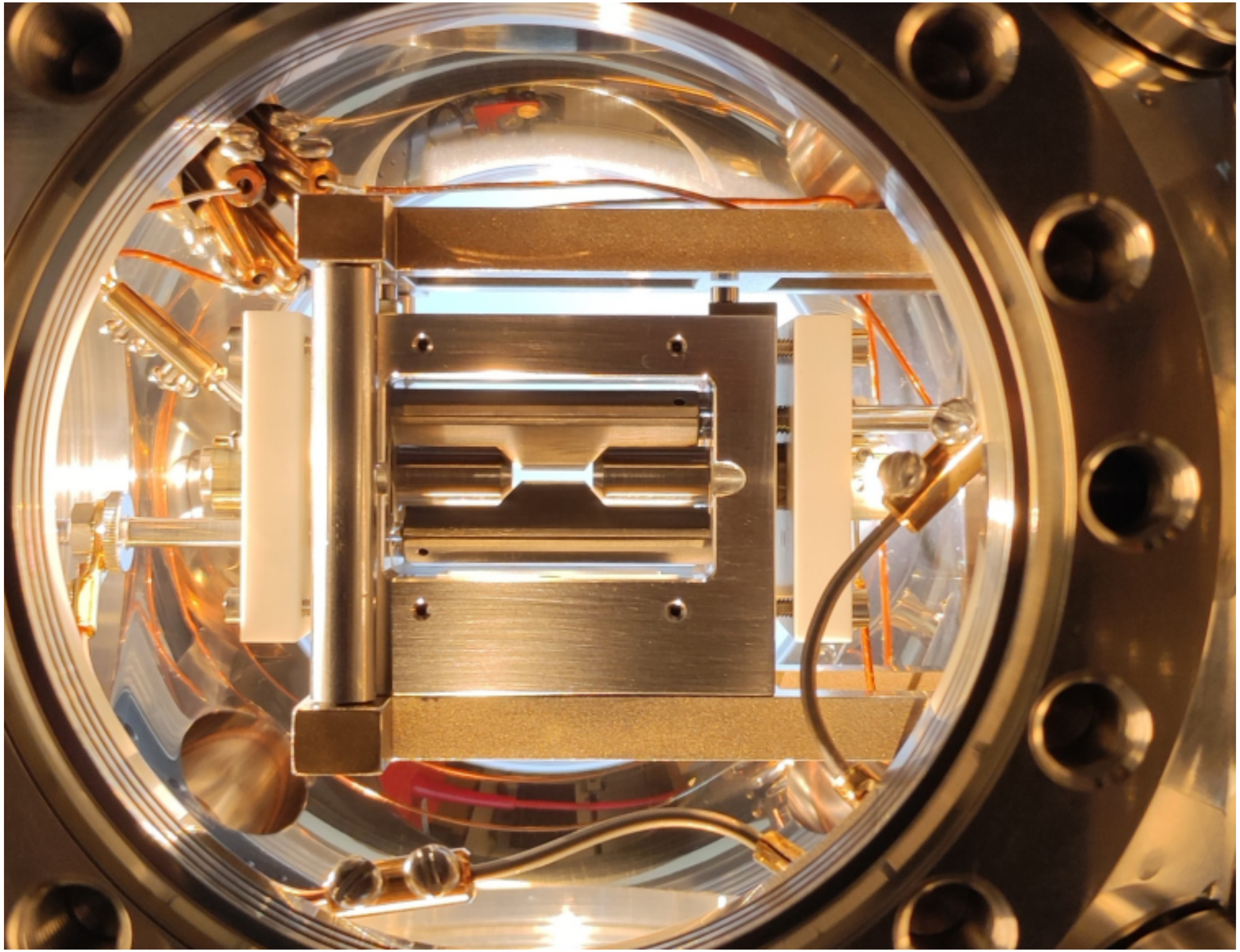
A trap
A vacuum chamber
Atoms
An ionization method
An observation method

Paul trap, mechanical analogue

How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

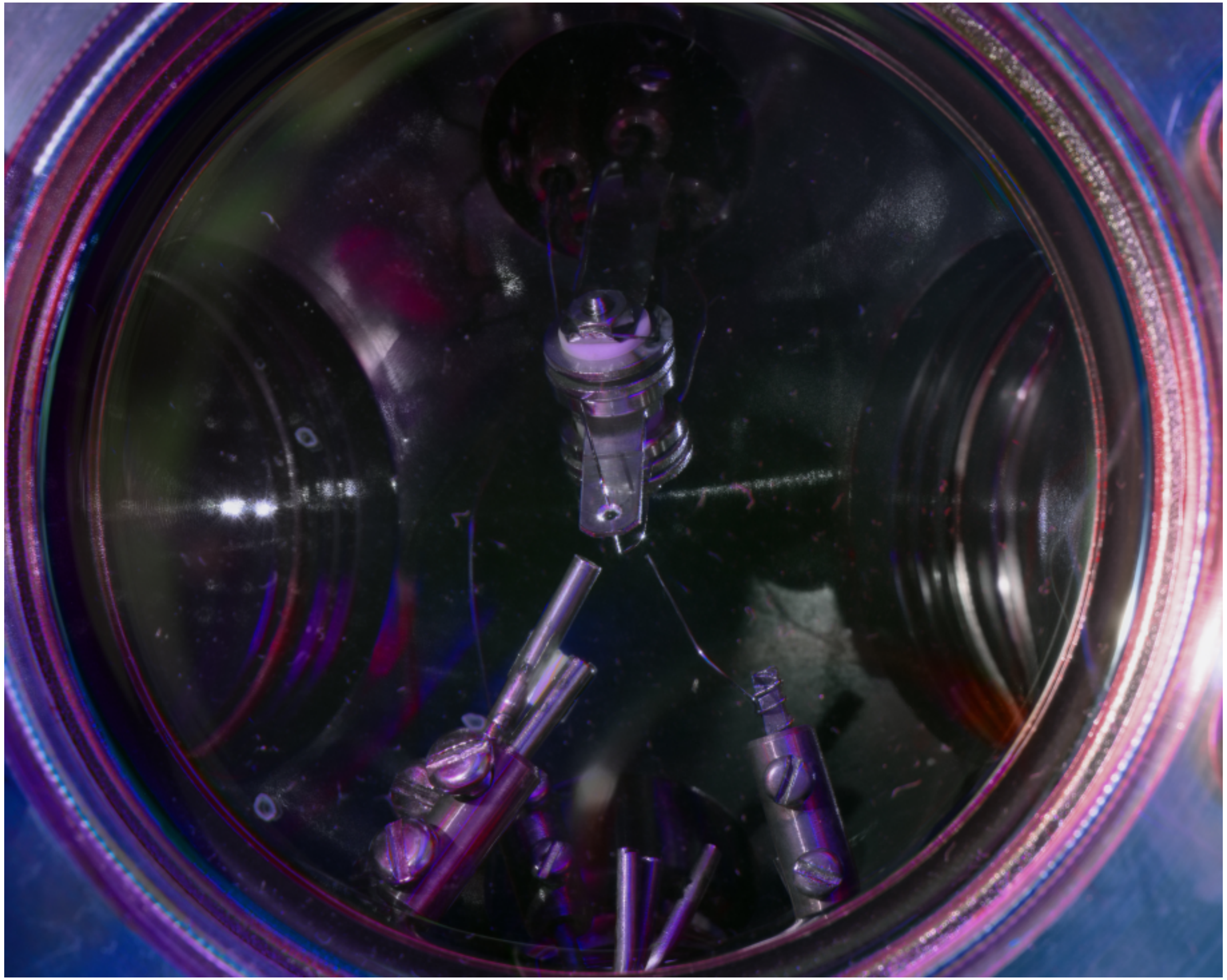
A linear Paul Trap



How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

An ring Paul Trap



How to trap ions

A trap
A trap

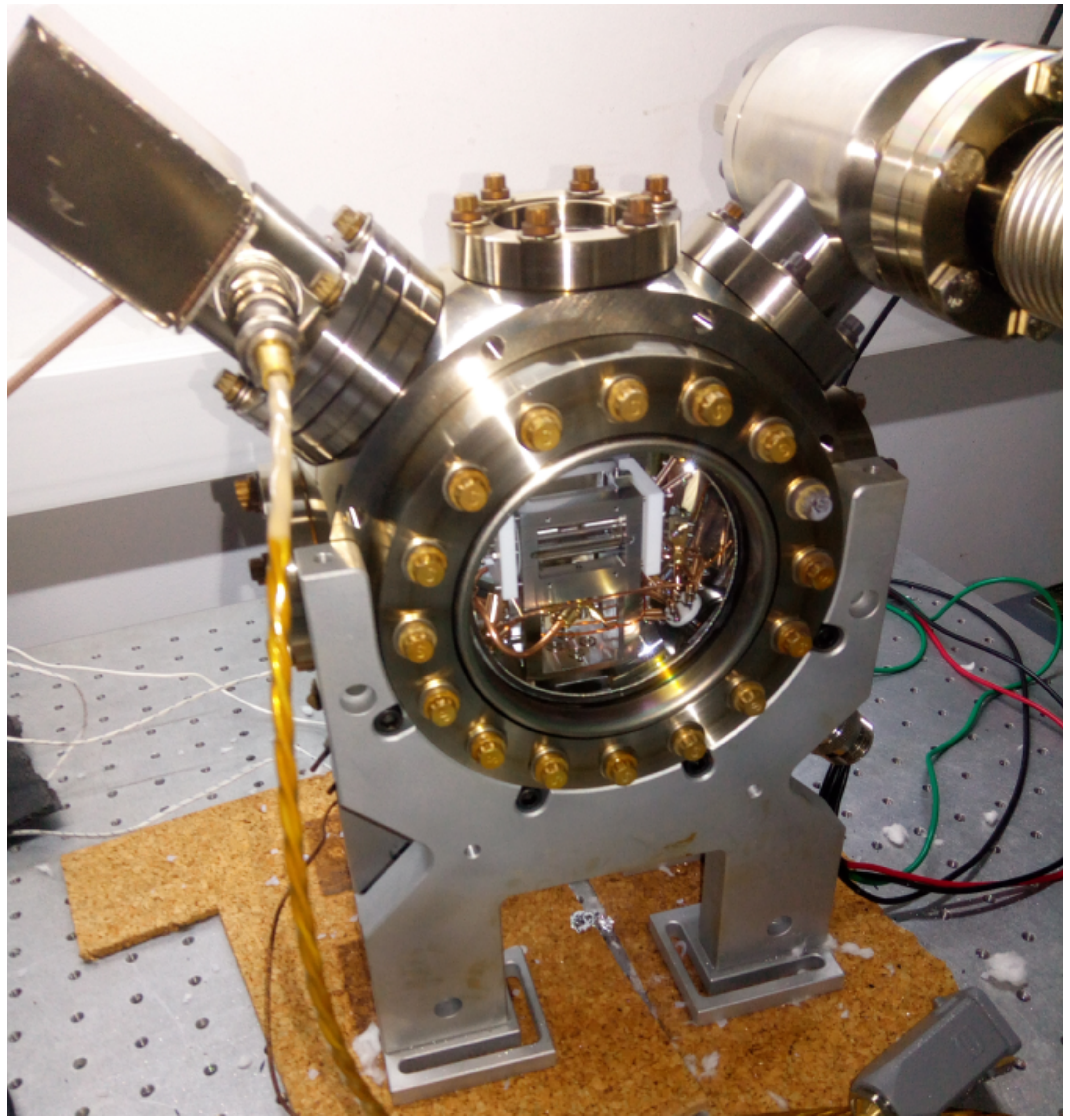
An ring Segmented Trap

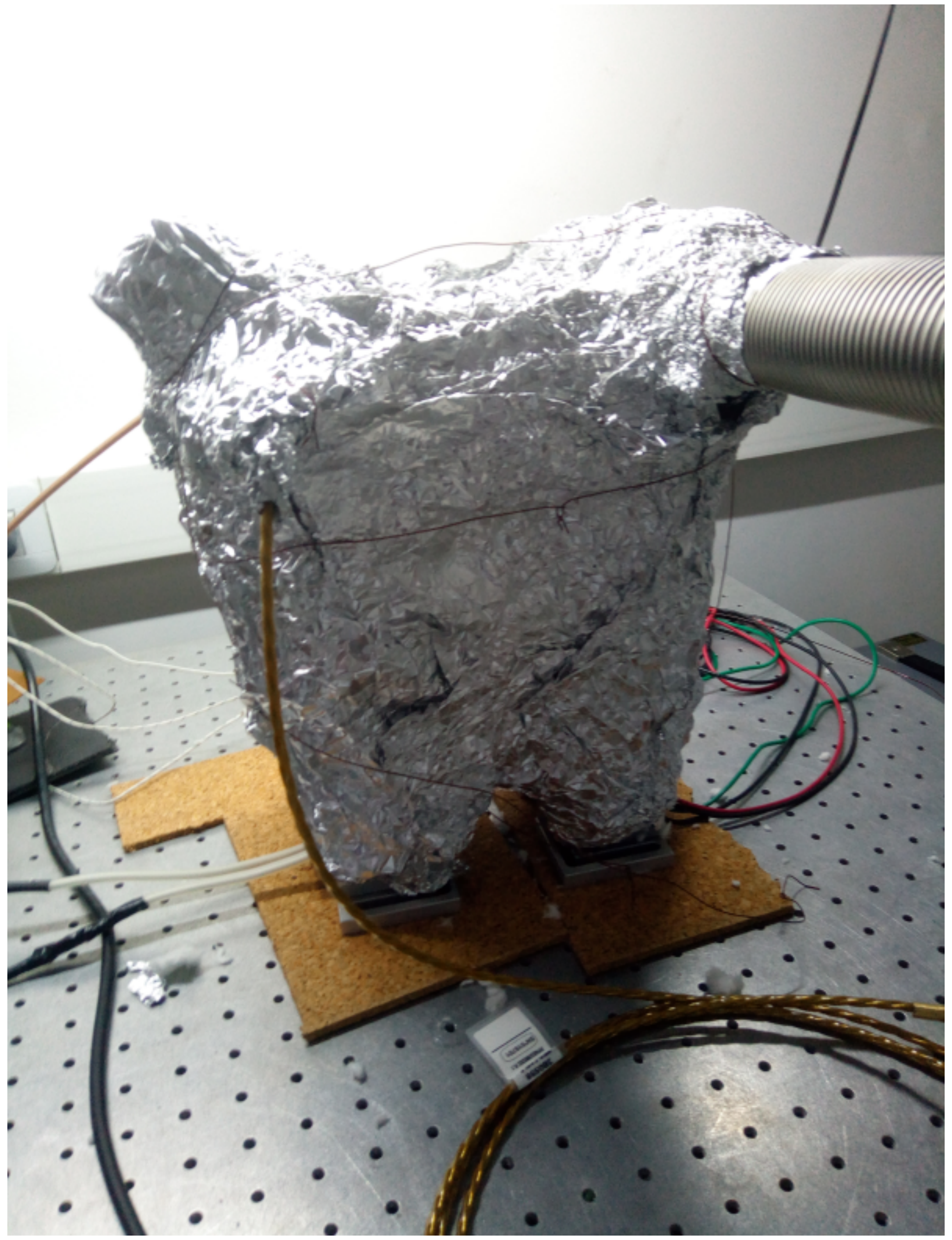
A vacuum chamber
Atoms
An ionization method
An observation method

How to trap ions

A trap
A vacuum chamber *Vacumm chamber, vacuum pumps, backing, and lots of patience!*
Atoms
An ionization method
An observation method

$$P < 10^{-11} \mathrm{mbar}$$

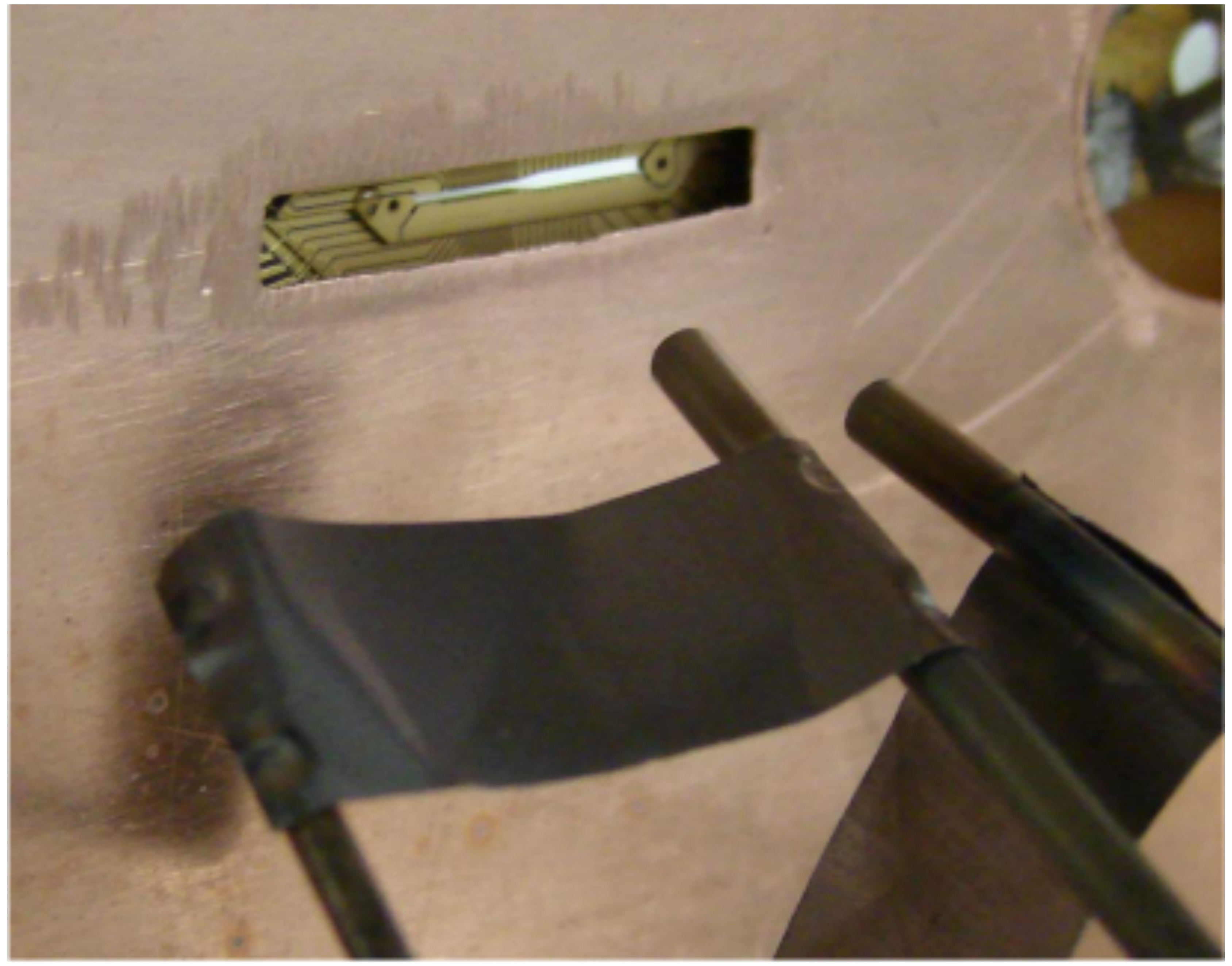


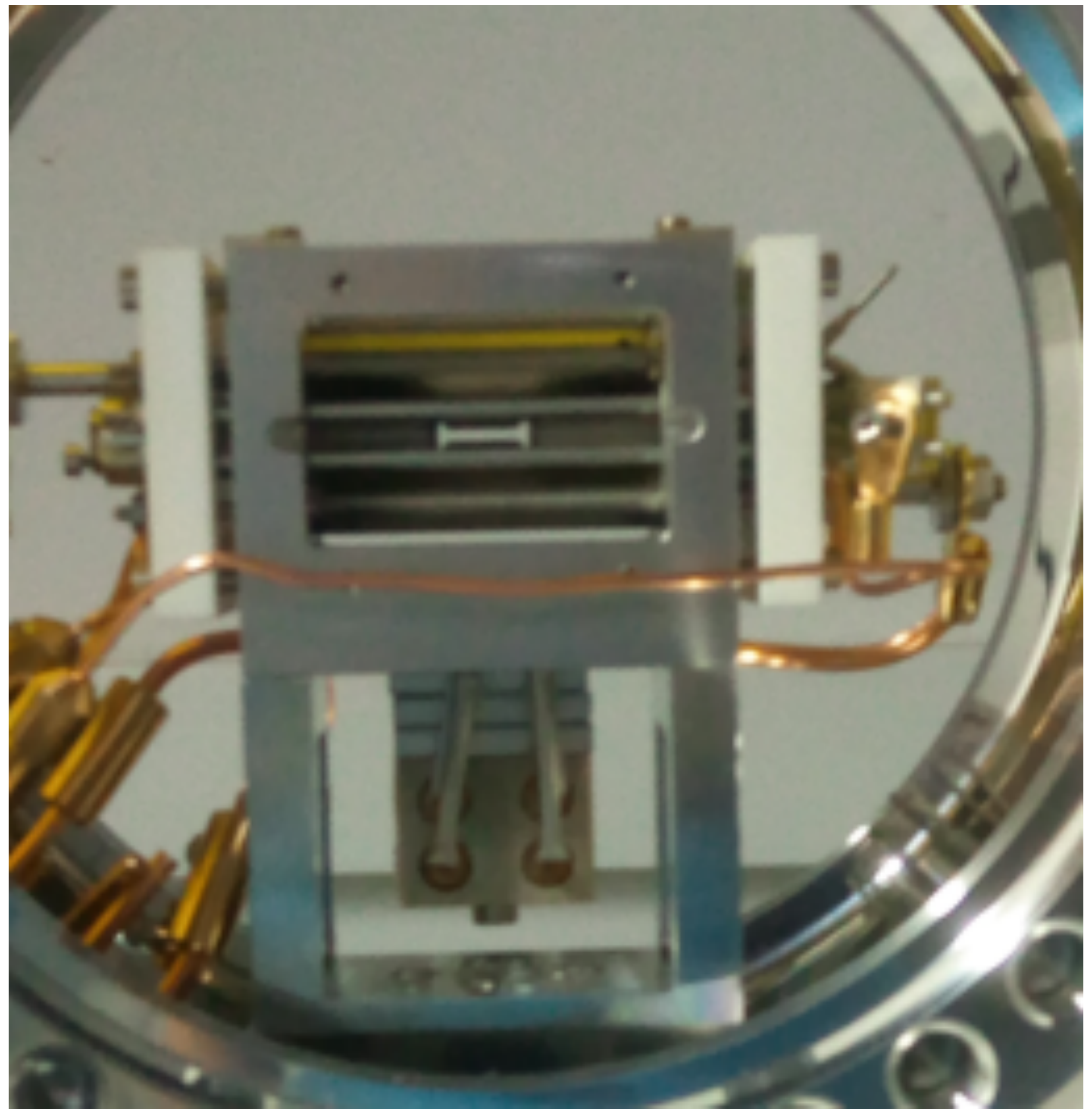



How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

Ovens: a source of neutral atoms in vacuum

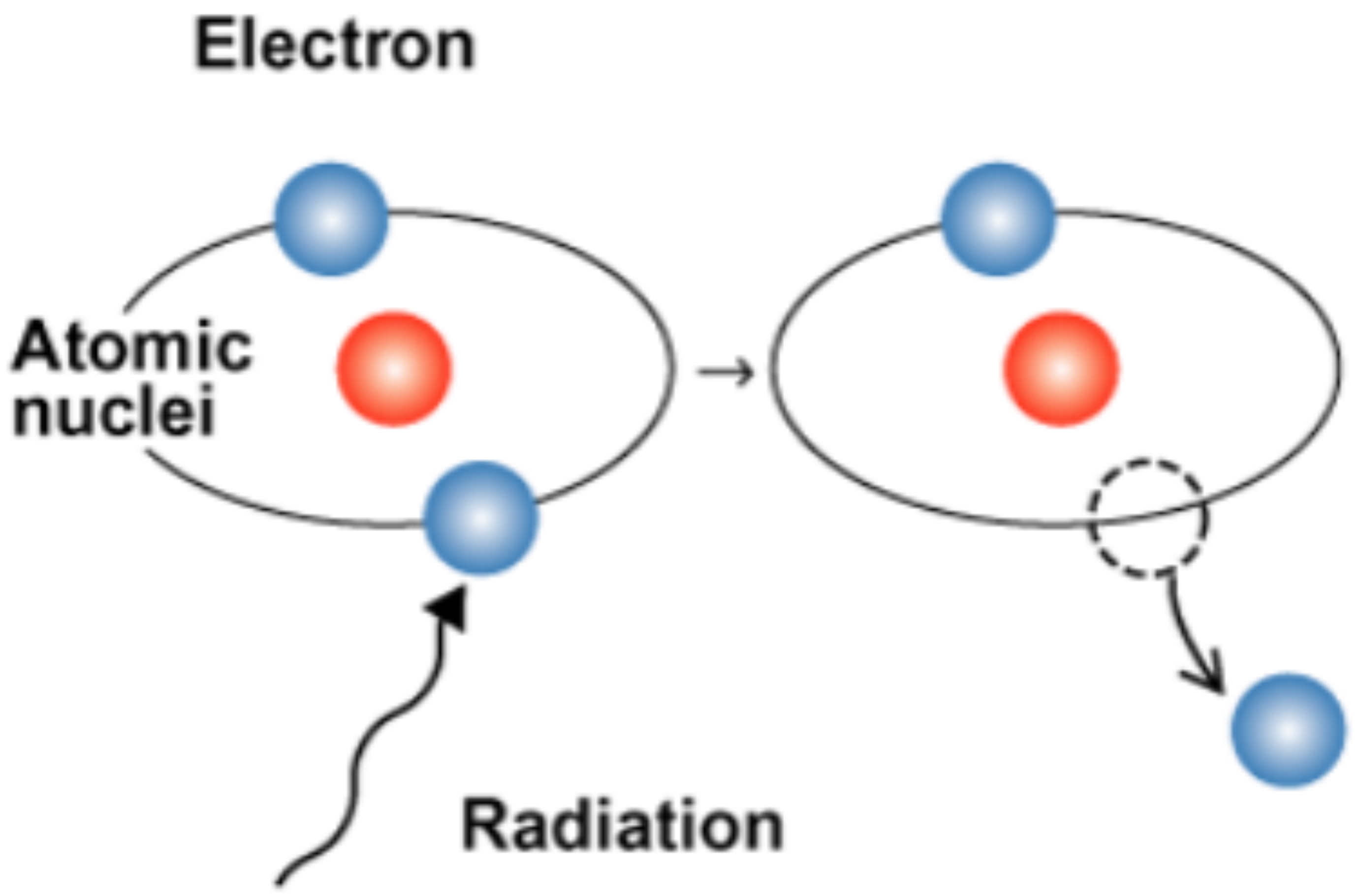


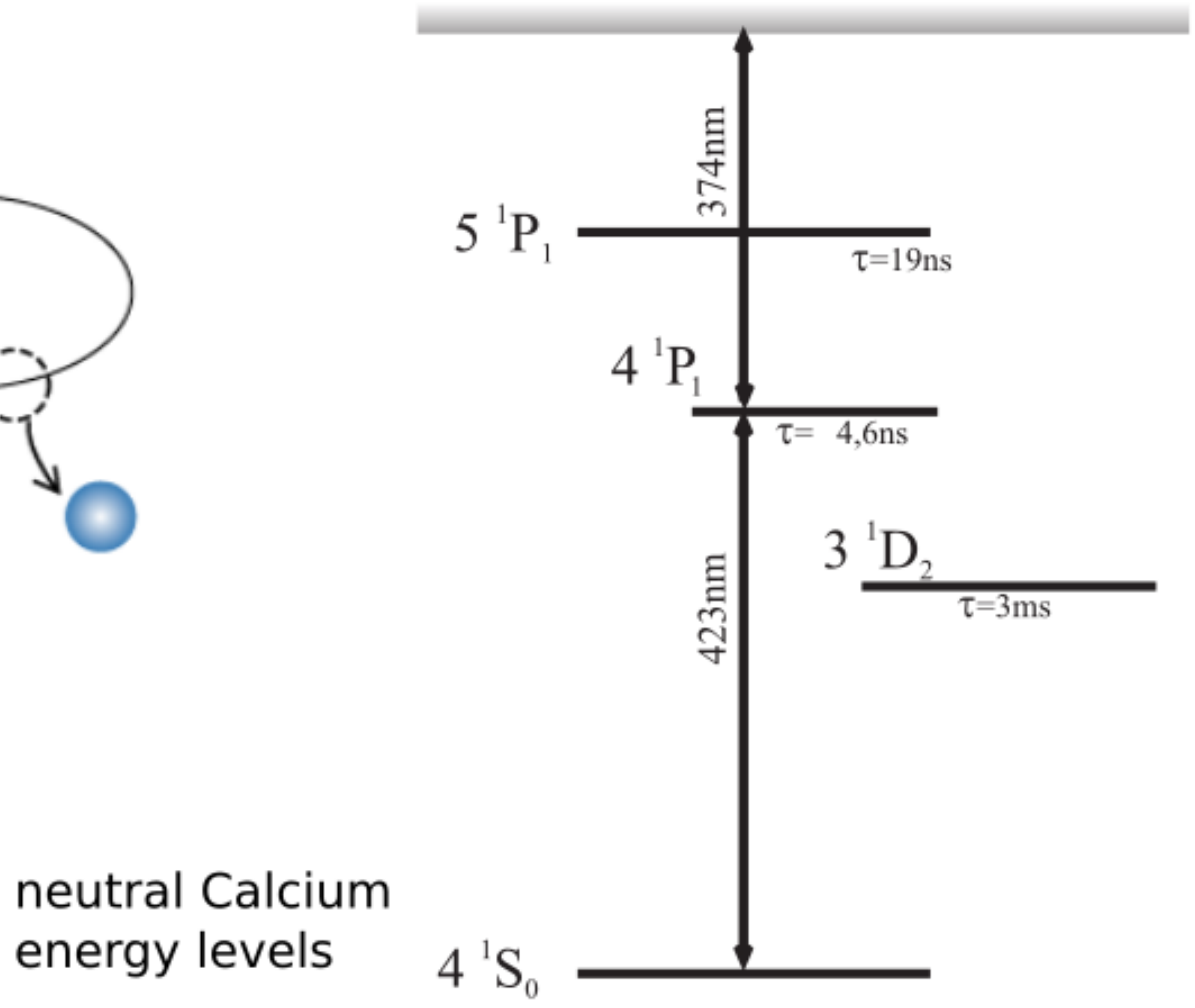


How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

Typically REMPI, two photon photoionization, but can also be otherwise…

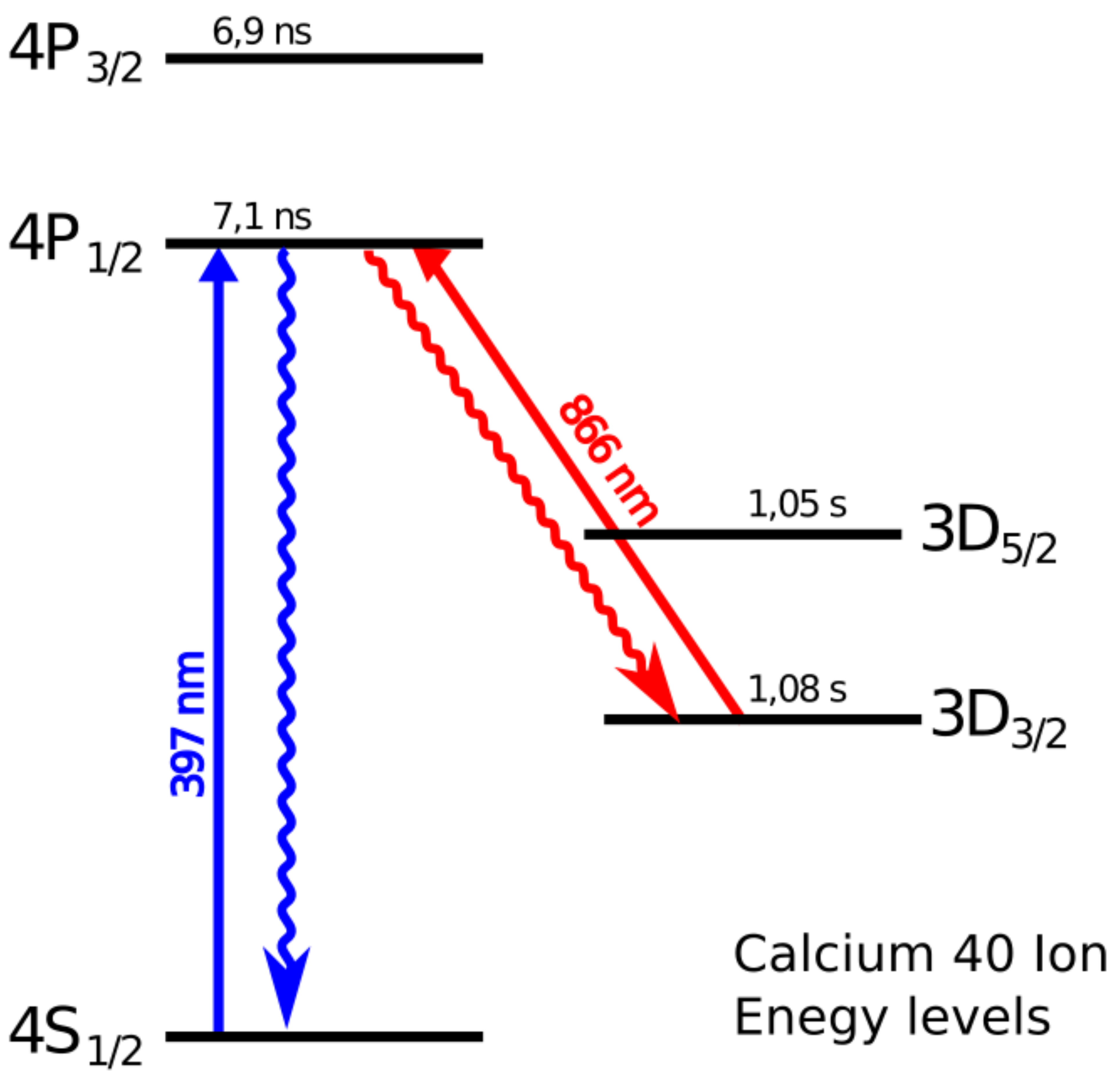




How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

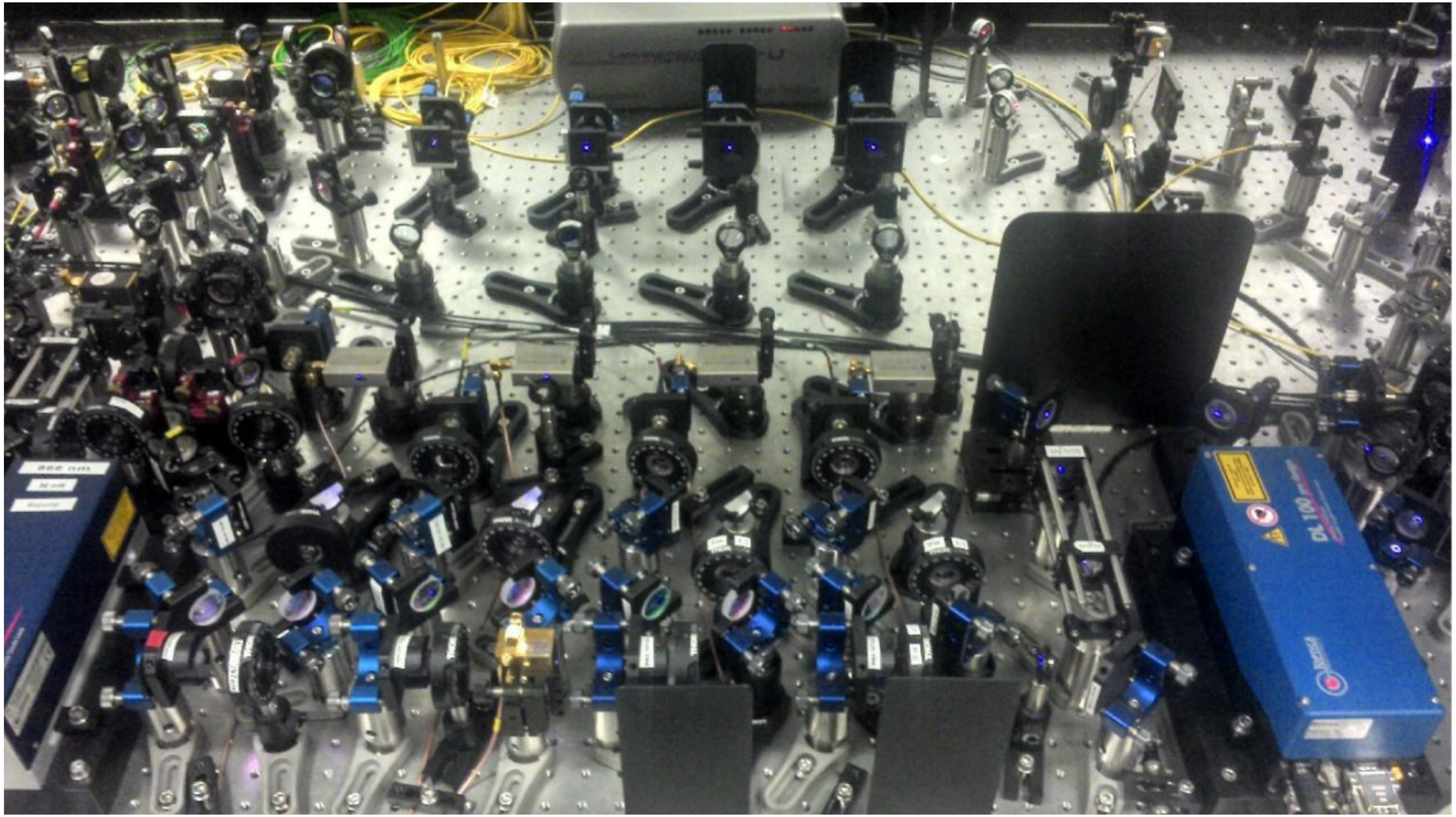
Resonance fluorescence, and Doppler cooling, plus extra "repumping"



How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

Lasers, lasers, lasers.
For cooling, ionizing, optical pumping, coherent control, etc.

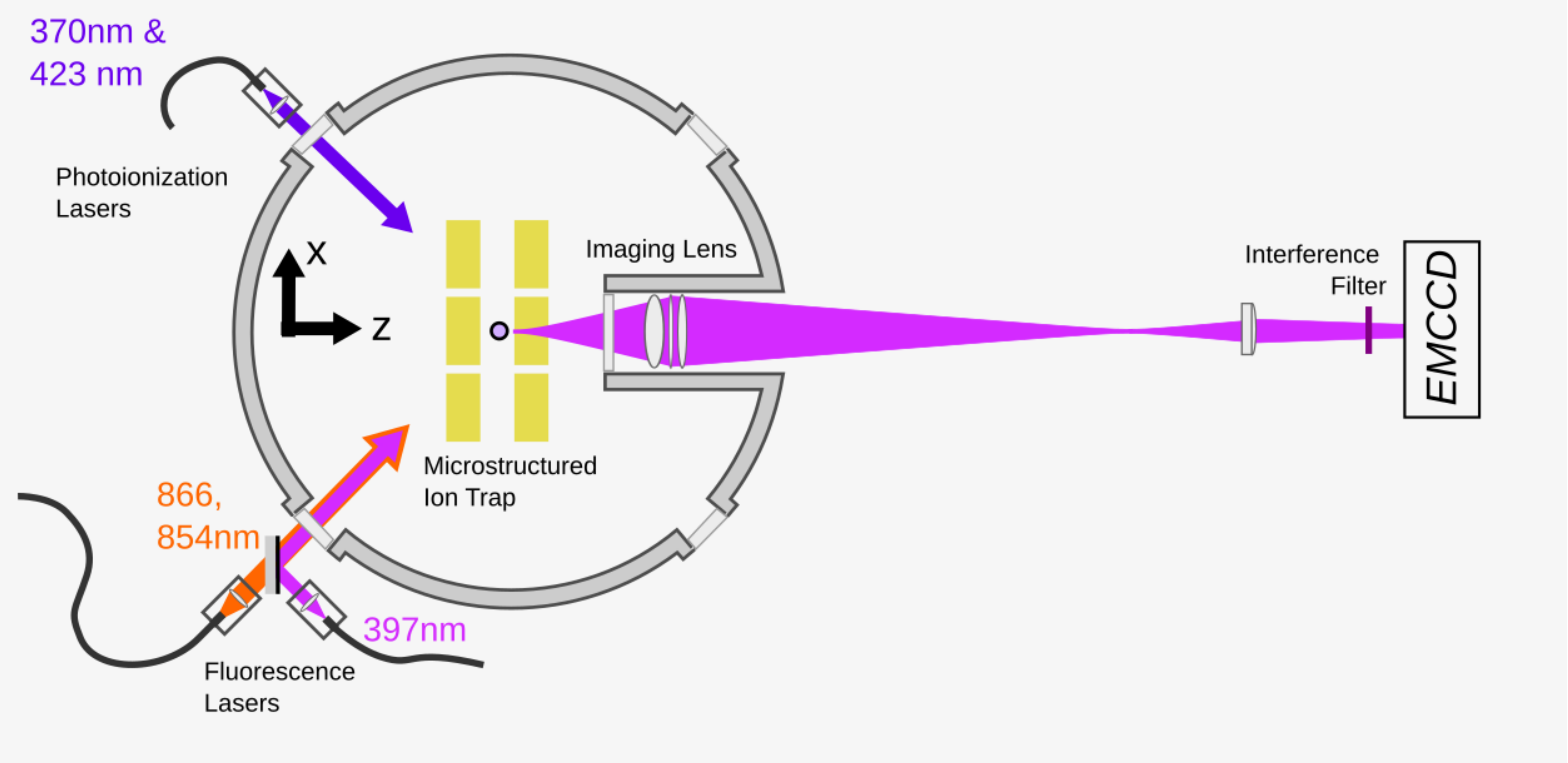


Frequency stabilized, power stabilized, polariztion controlled.
Switchable in us, in amplitude and frequency.

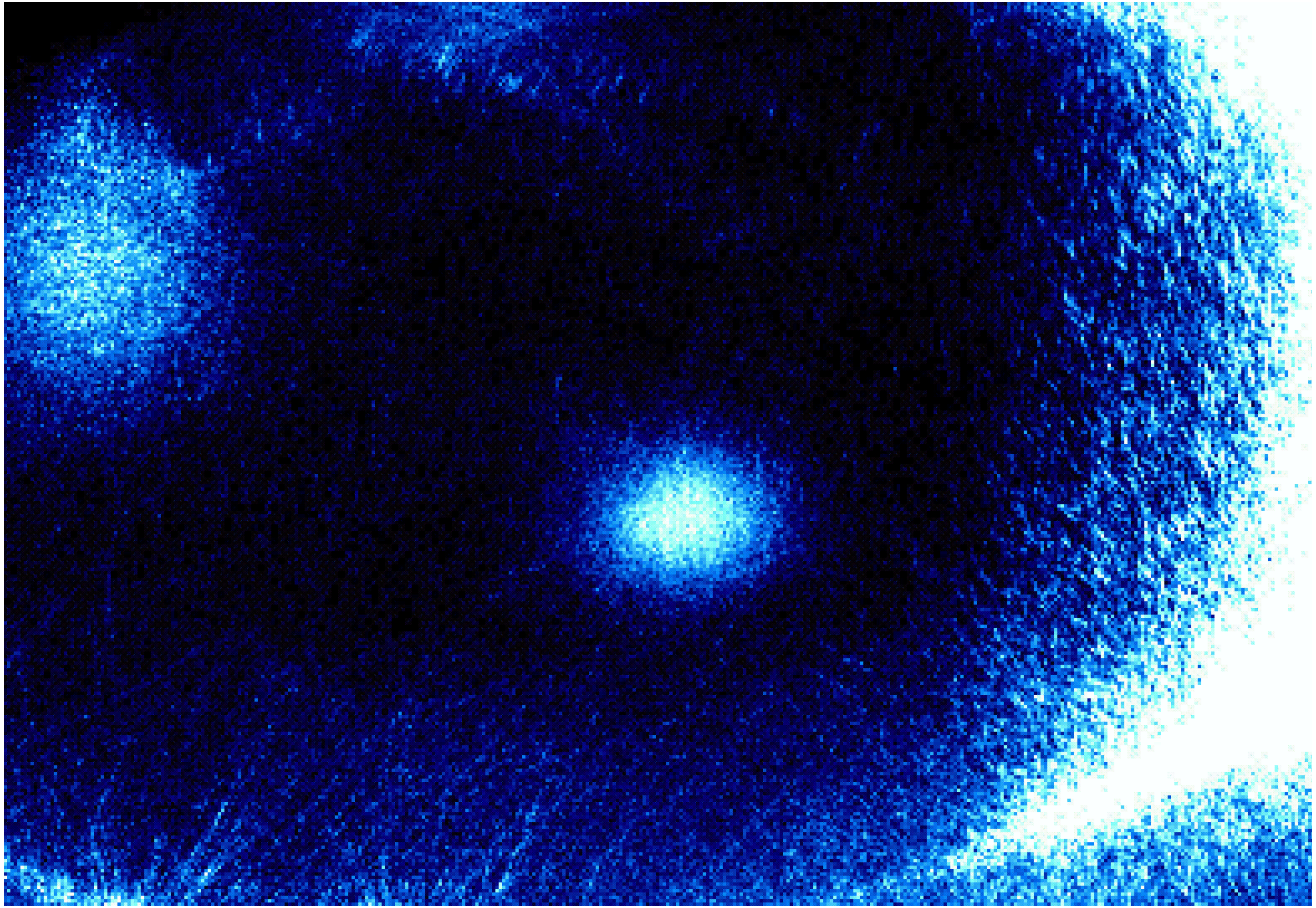
How to trap ions

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

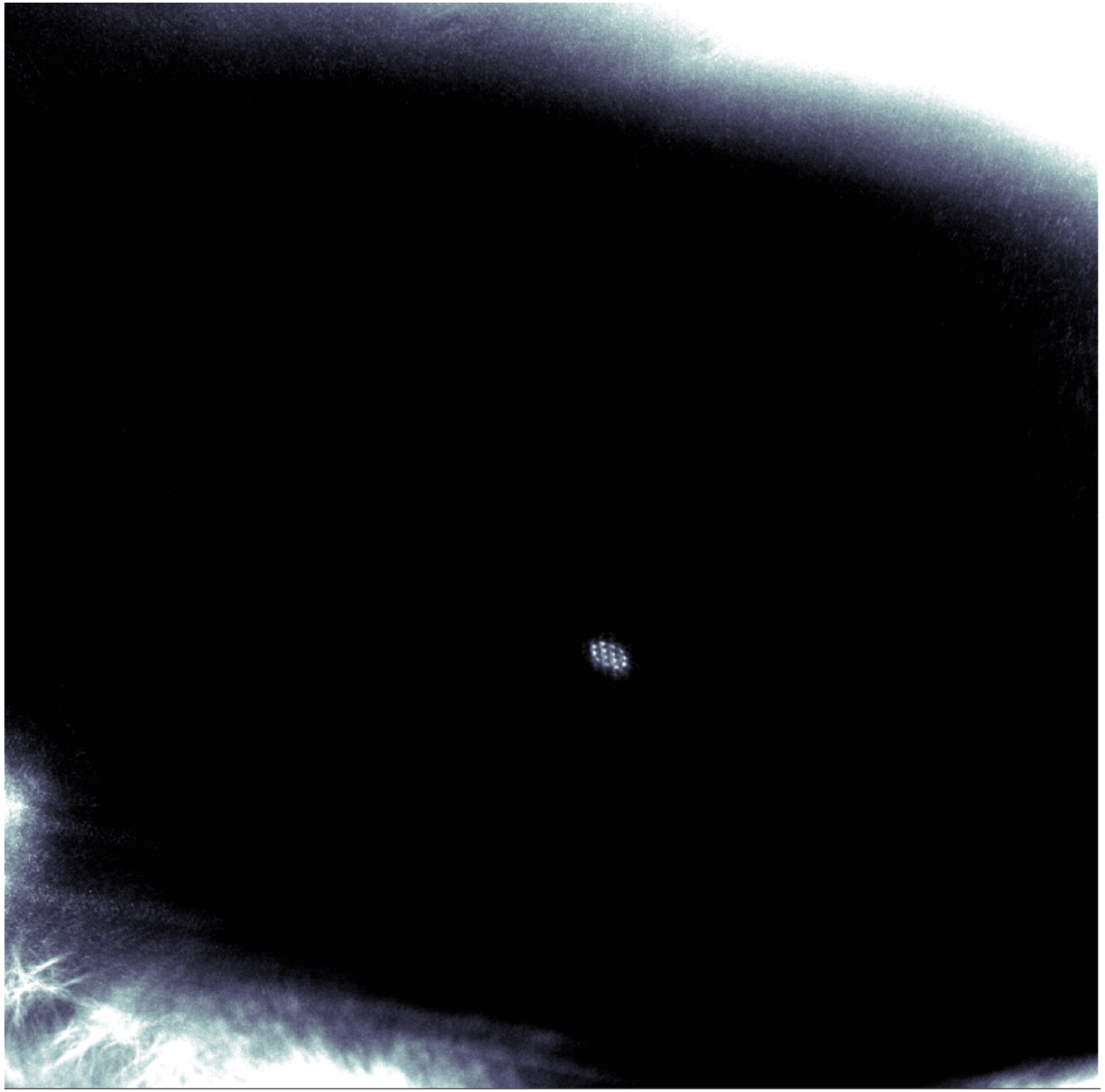
Trap, lasers, chamber and observation optics



How to trap ions - voilà

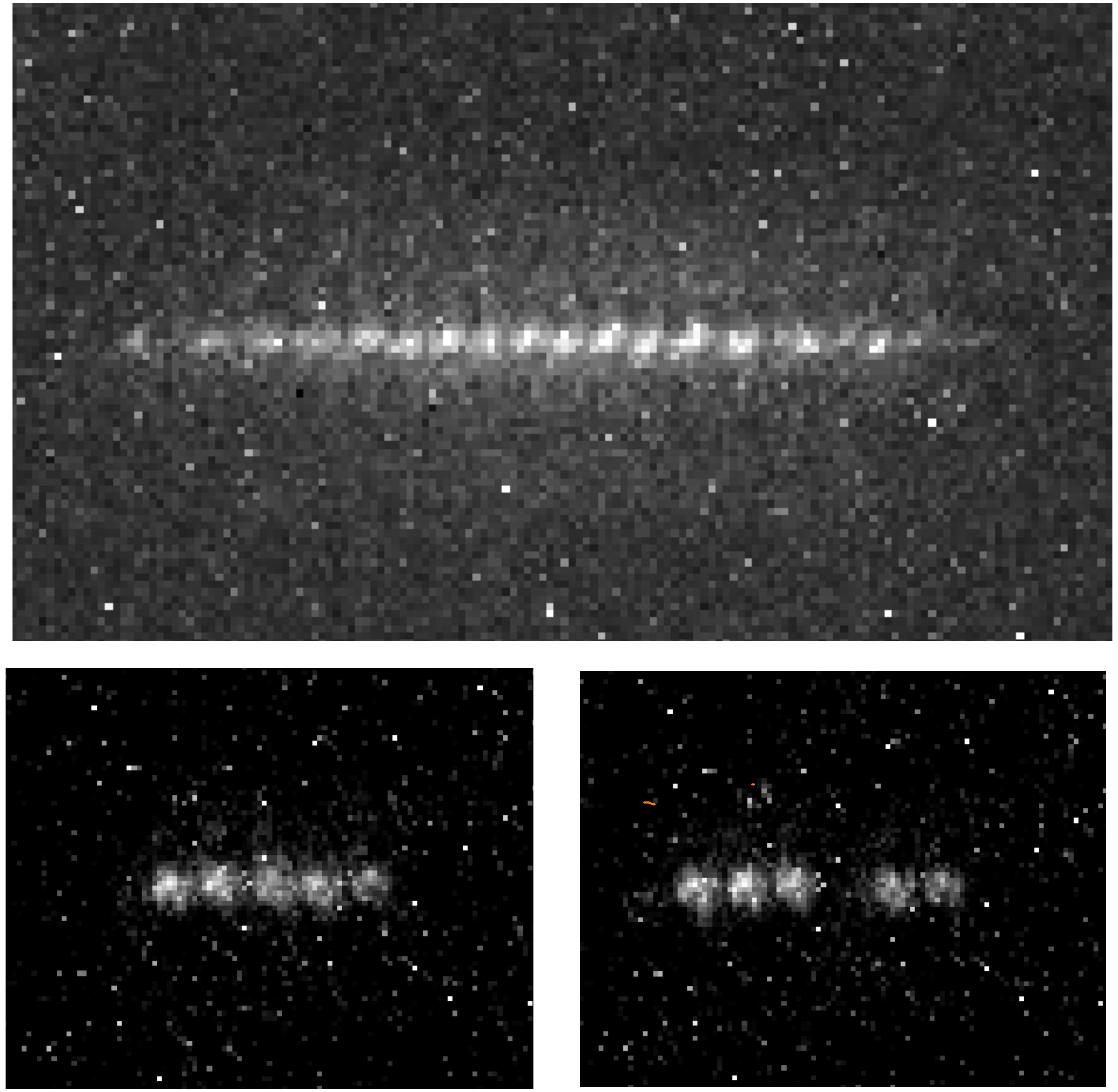


How to trap ions - voilà

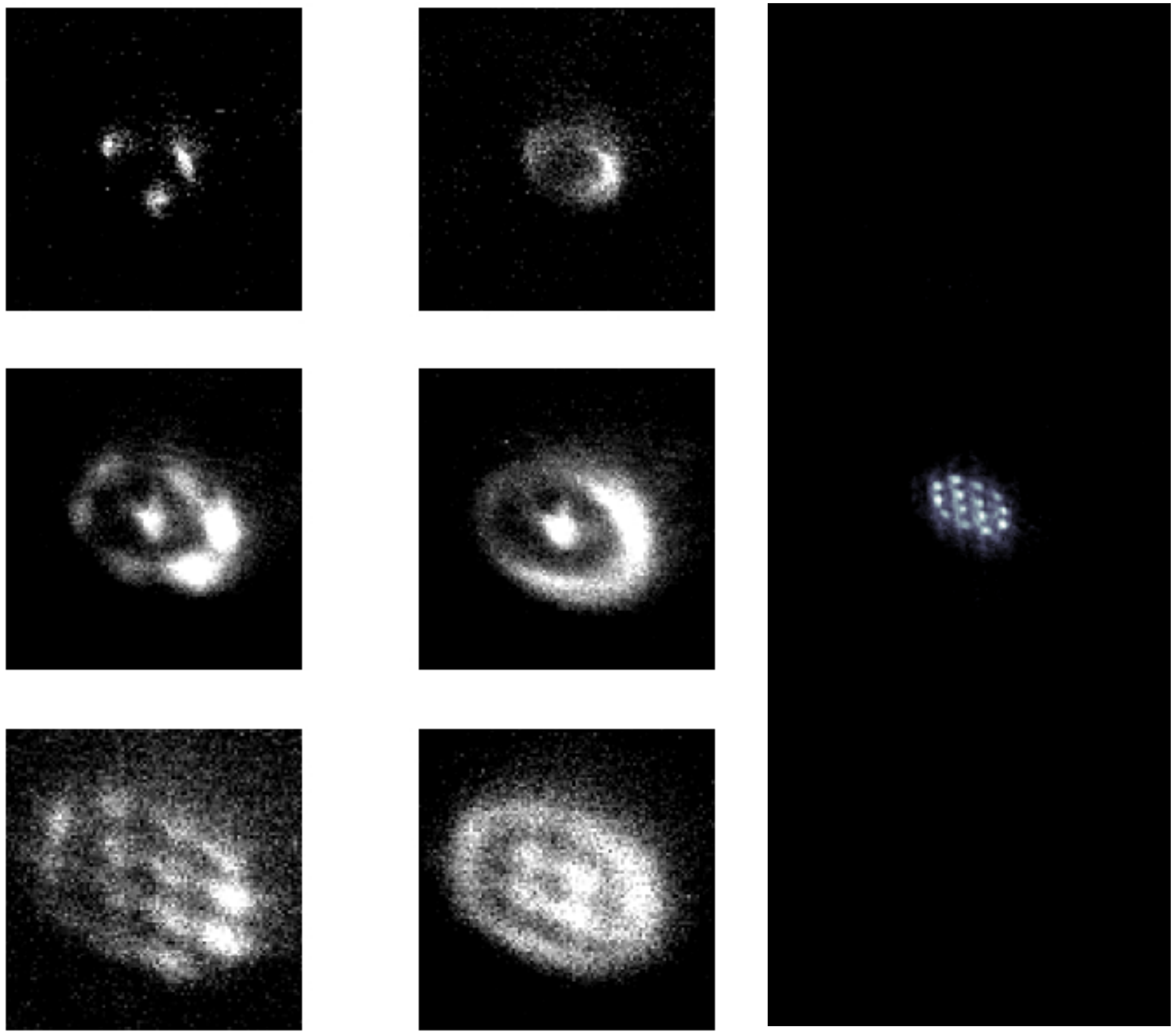


How to trap ions - voilà

Linear trap crystals



Ring trap crystals



videos and imagis ov moving ions in segmented traps

Day Two

Part 3

Orbital angular momentum and selection rules in atoms

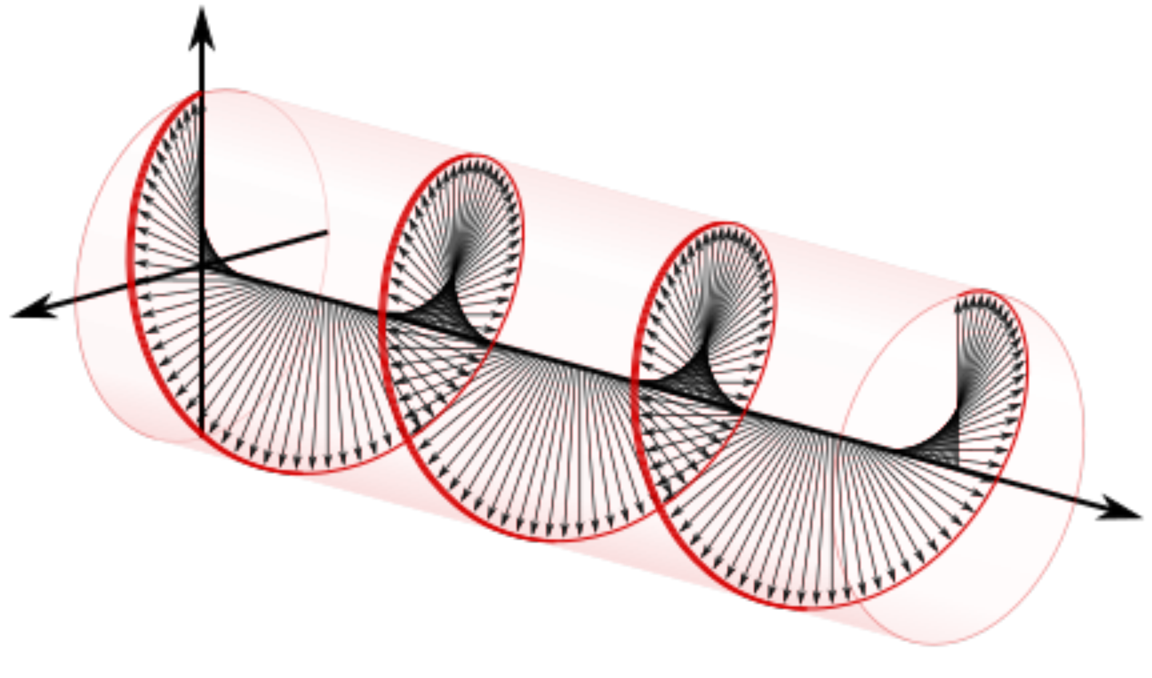
Twisting in the dark what about the (orbital) angular momentum?

Intrinsic, polarization

$$A = A_0(\hat{x} \pm i\hat{y})$$

$$\rightarrow J_z = \pm\hbar$$

$$\Delta m_J = \pm 1$$



Historical remarks

- The experiments of Hanle & of Bär.
-- Anomalies in Raman scattering.

- The conclusion of Raman, Kastel and Cabannes.
-- Wait, recalculating!

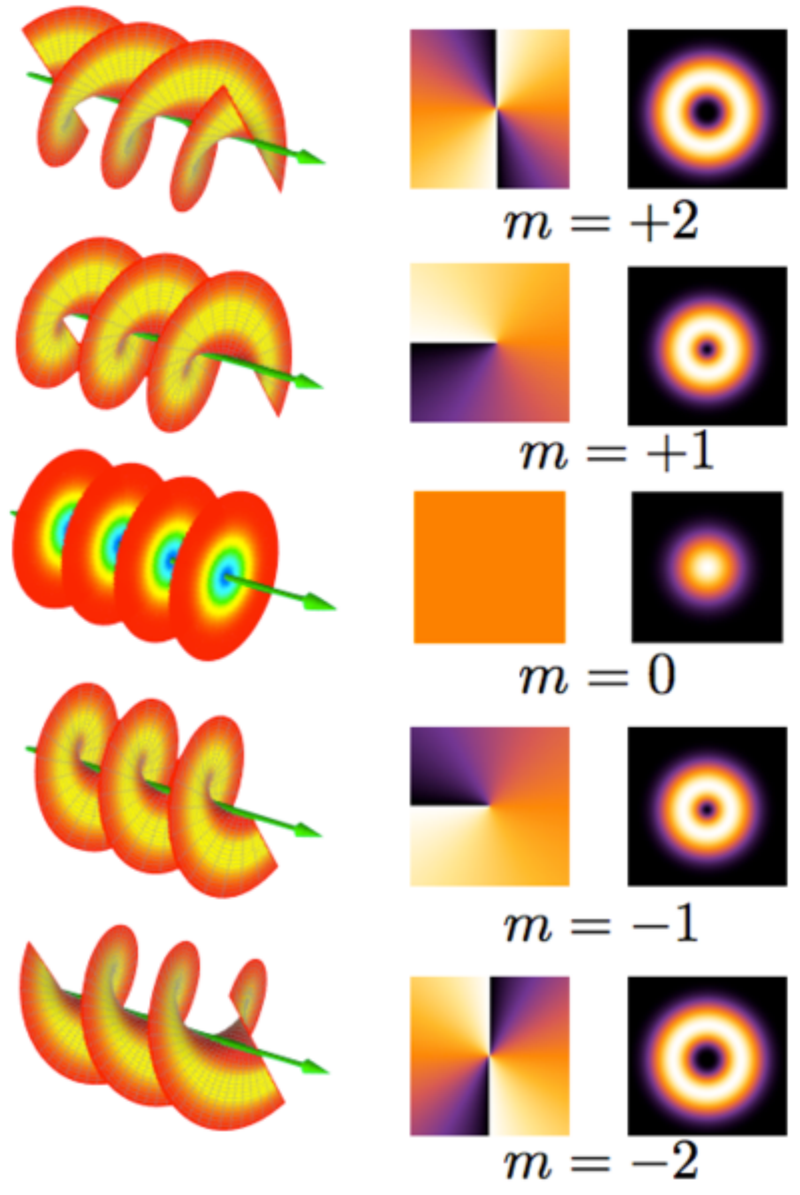
- The expriments of Beth.
-- Let's go macroscopic.

Extrinsic, orbital angular momentum

$$A = A_0(\hat{x} \pm i\hat{y})e^{il\phi}$$

$$\rightarrow J_z = \pm\hbar + l\hbar$$

$$\Delta m_J = \pm 1 + l \quad \cdots ?$$



Historical remarks

- The paper PRA 45, 8185 (1992)
"Orbital angular momentum of light and
the transformation of Laguerre-Gaussian laser modes"
by Allen, Beijersbergen, Spreeuw and Woerdman

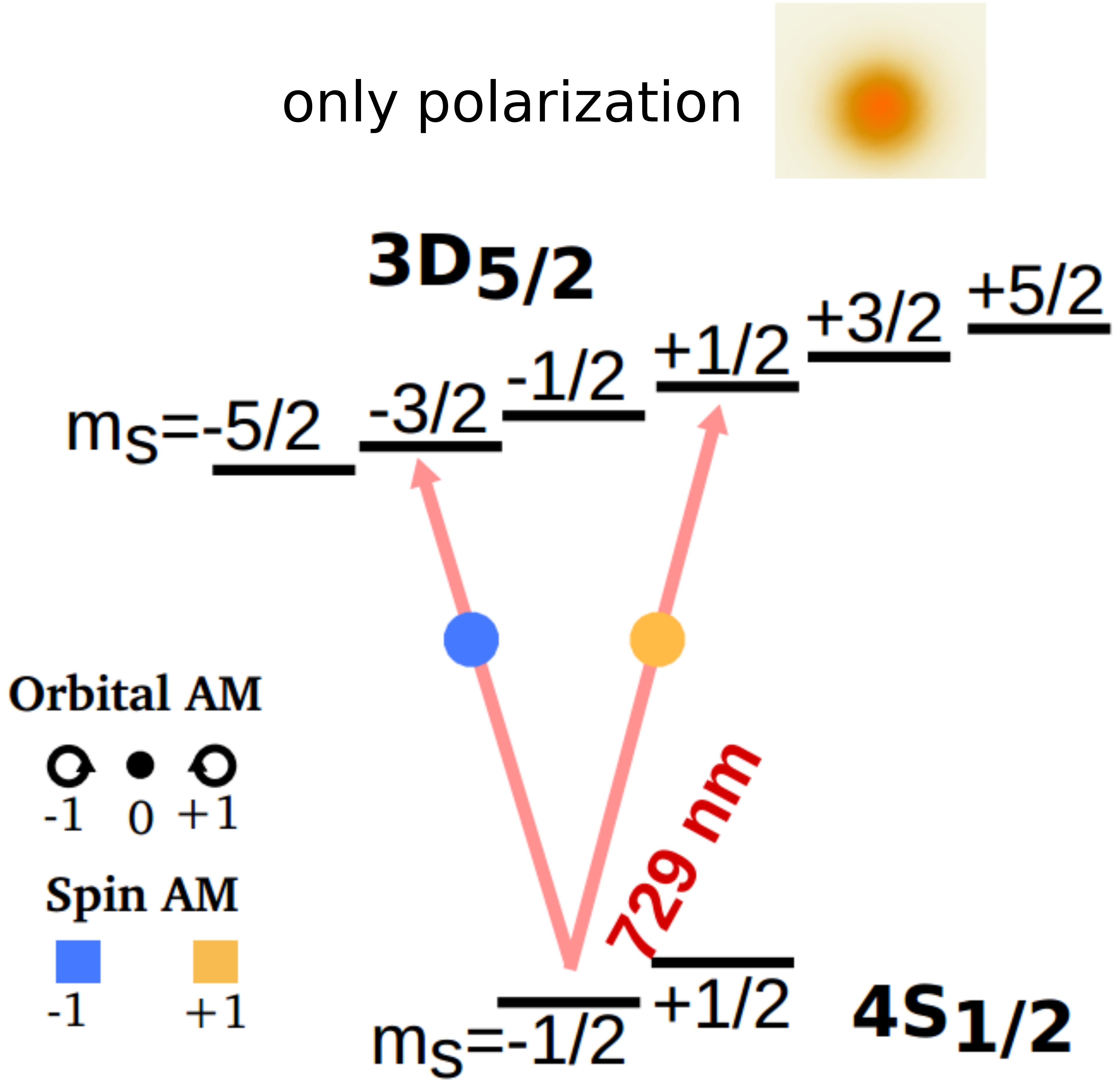
- The first demonstration by H. Rubenstein-Dunlop

- The many failed attempts to observe optical activity.

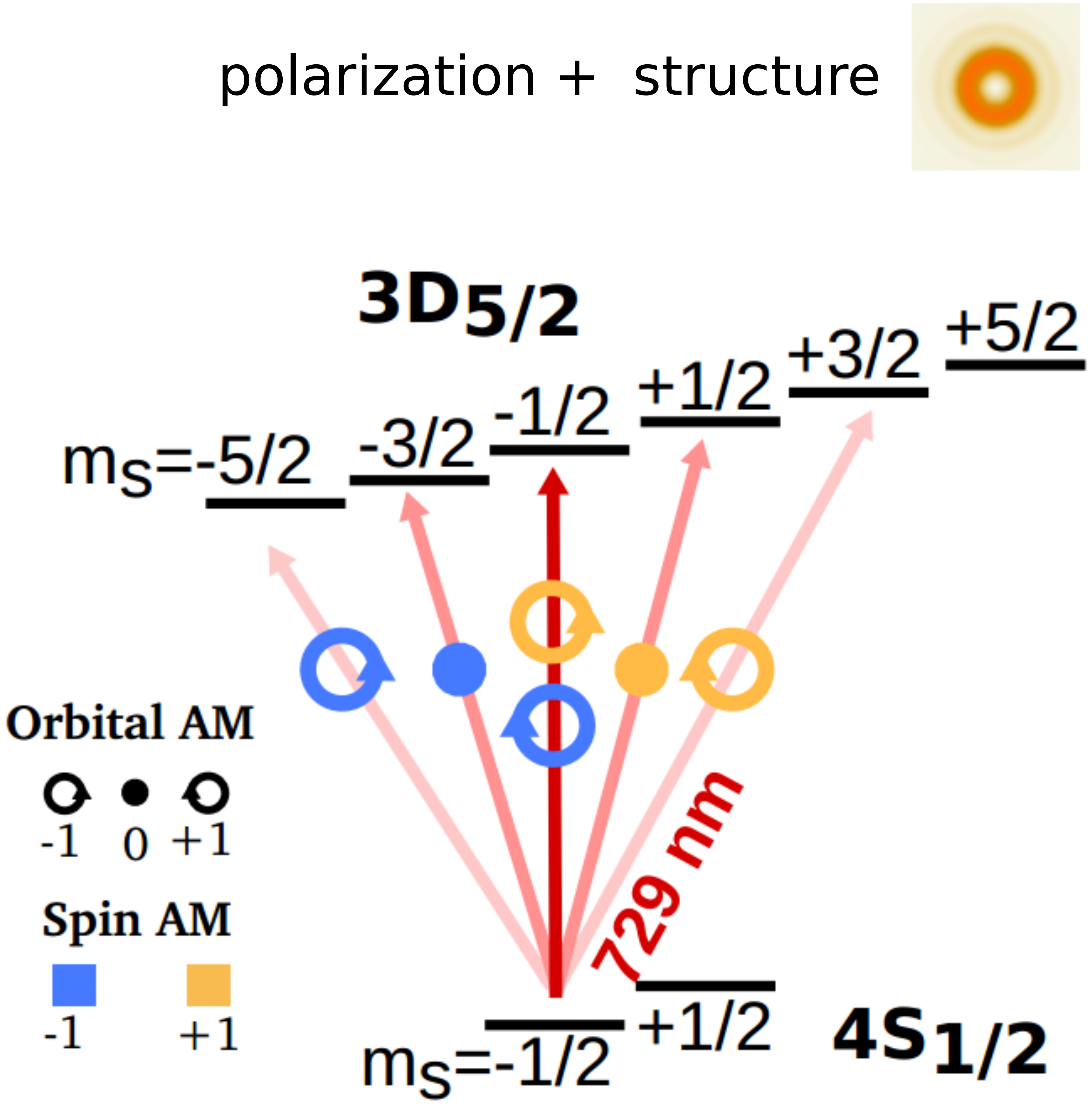
Christian Schmiegelow - Universidad de Buenos Aires

Twisting in the dark selection rules, for a rotationally symmetric system B||k

only polarization



polarization + structure



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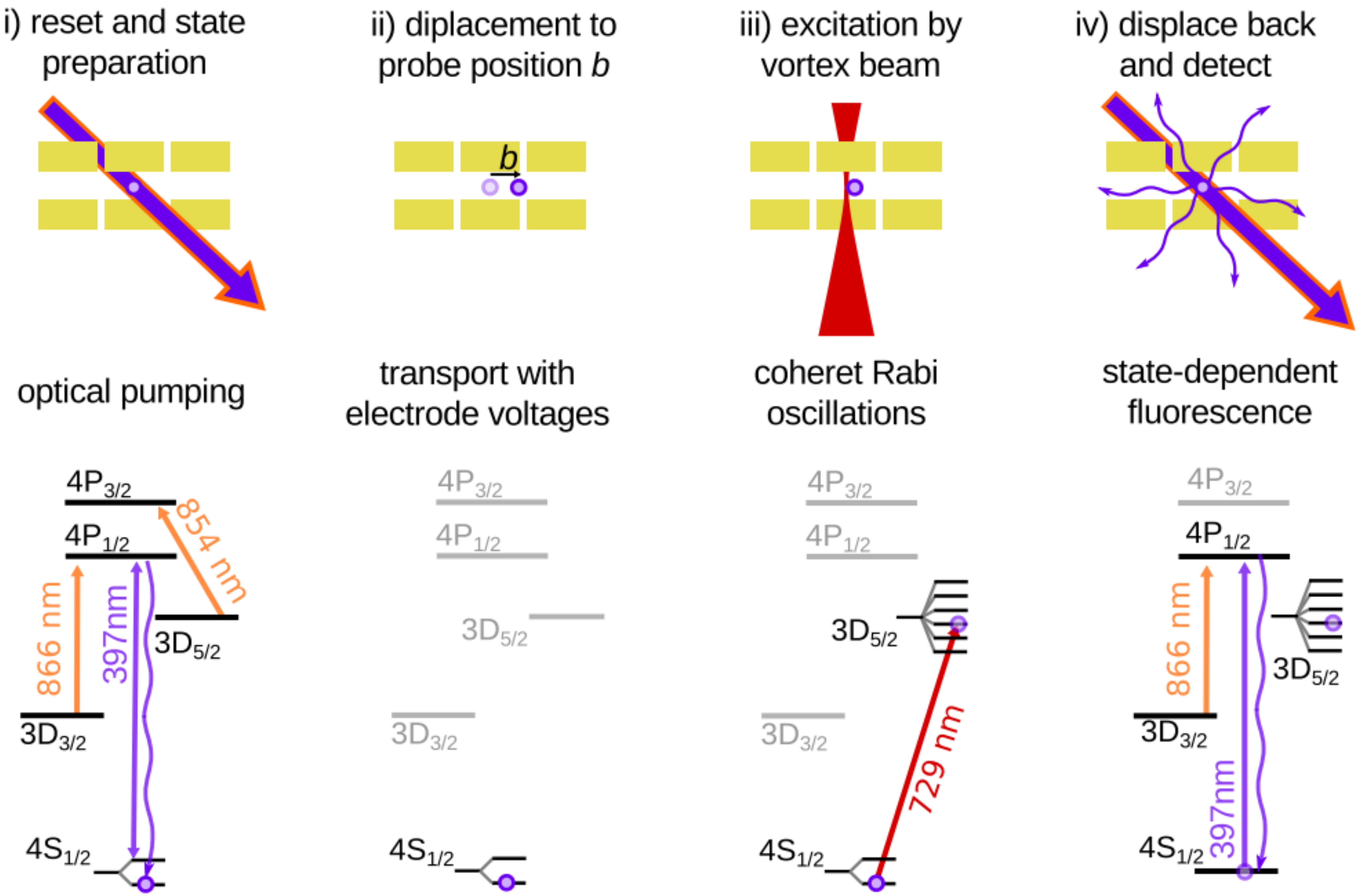
Twisting in the dark

selection rules, for a rotationally symmetric system B||k



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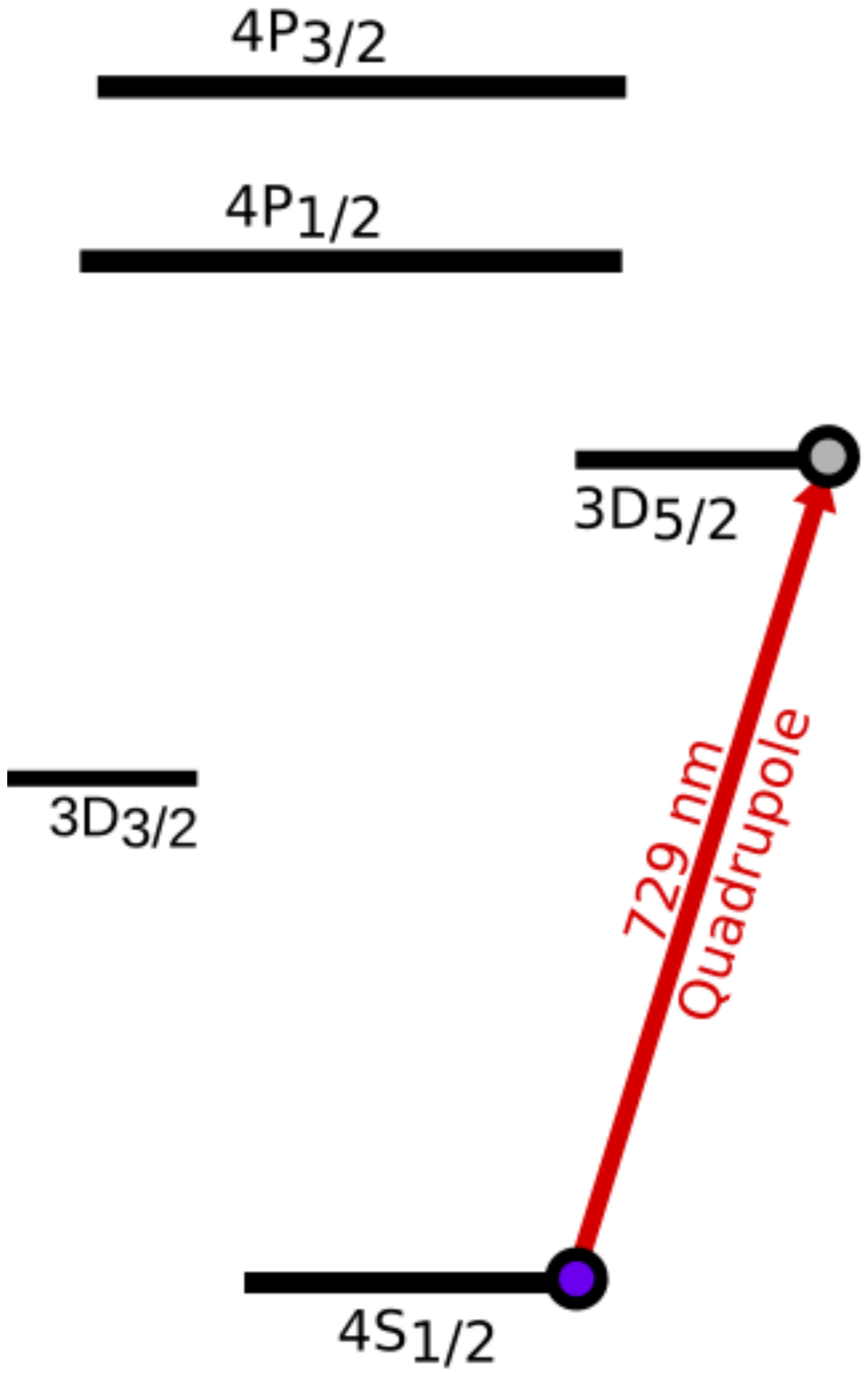
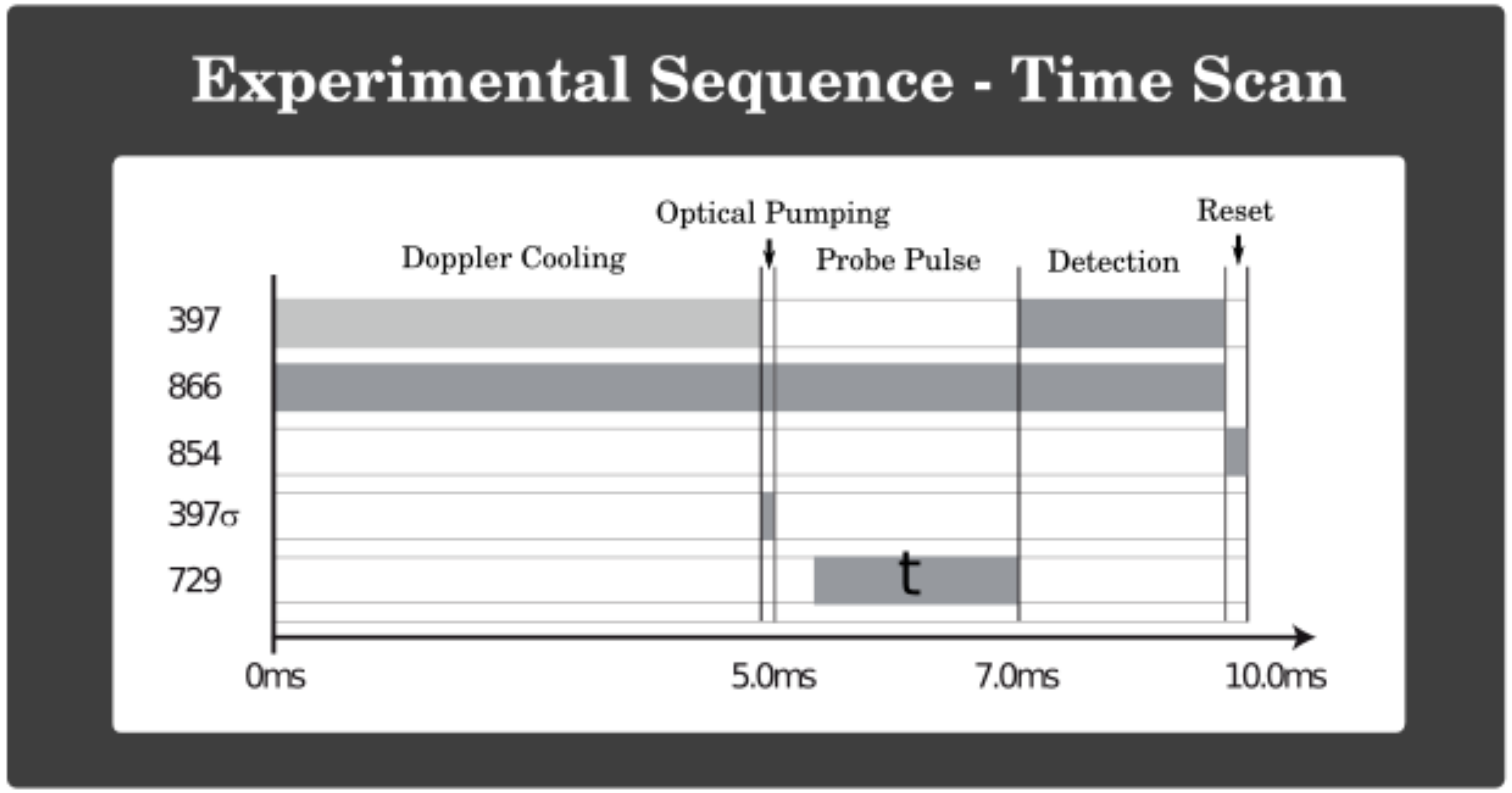
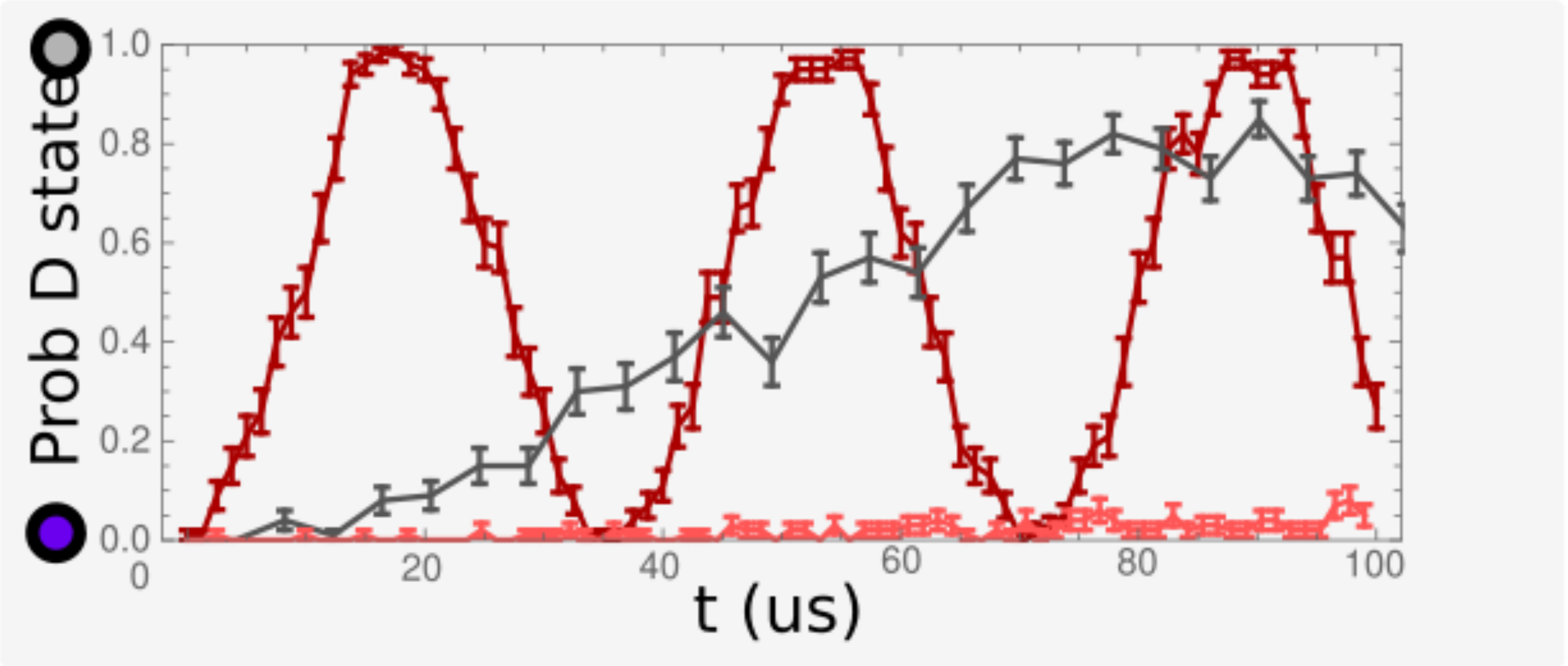
Twisting in the dark selection rules, for a rotationally symmetric system B||k







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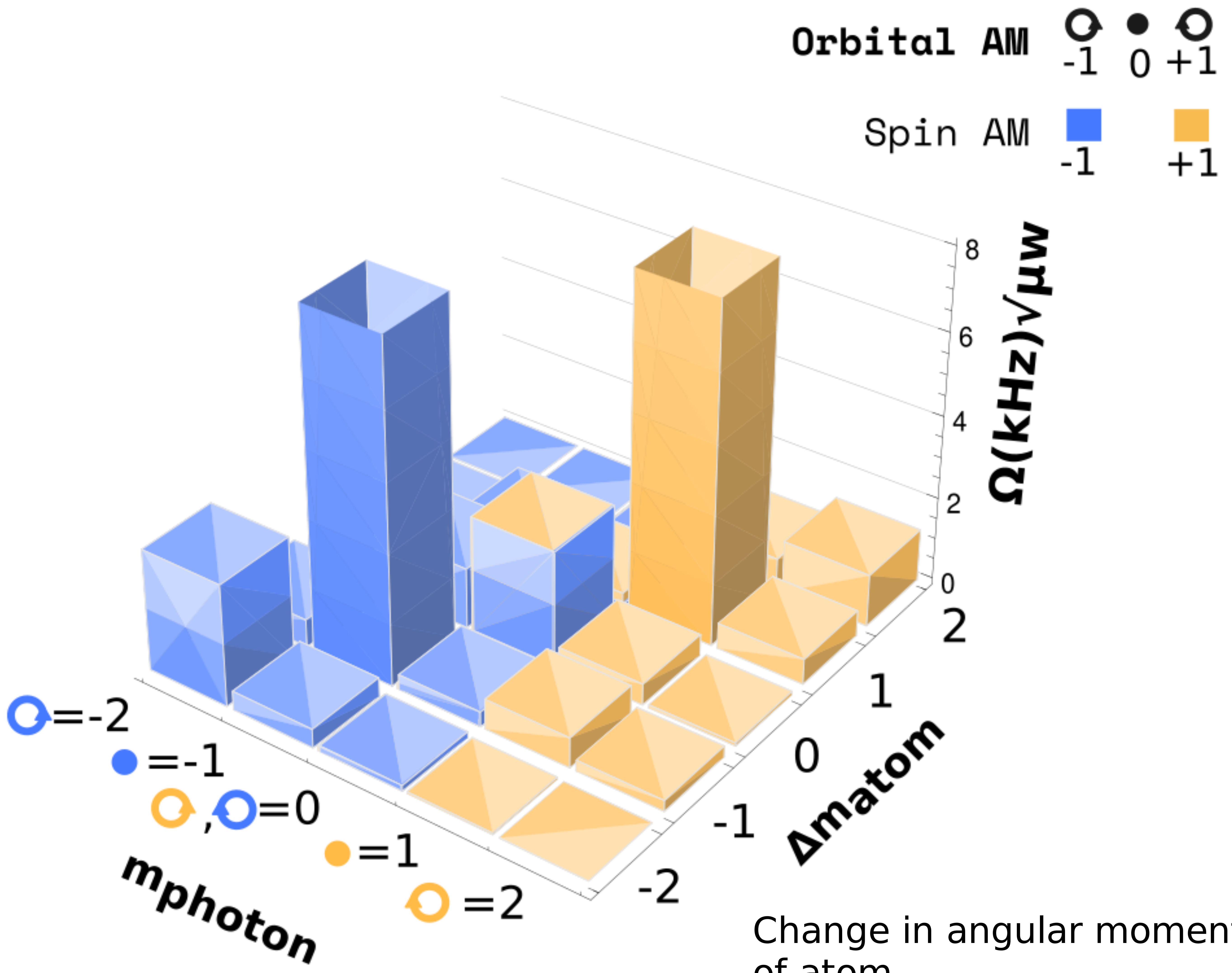
Twisting in the dark Results

Rabi frequencies for each transition



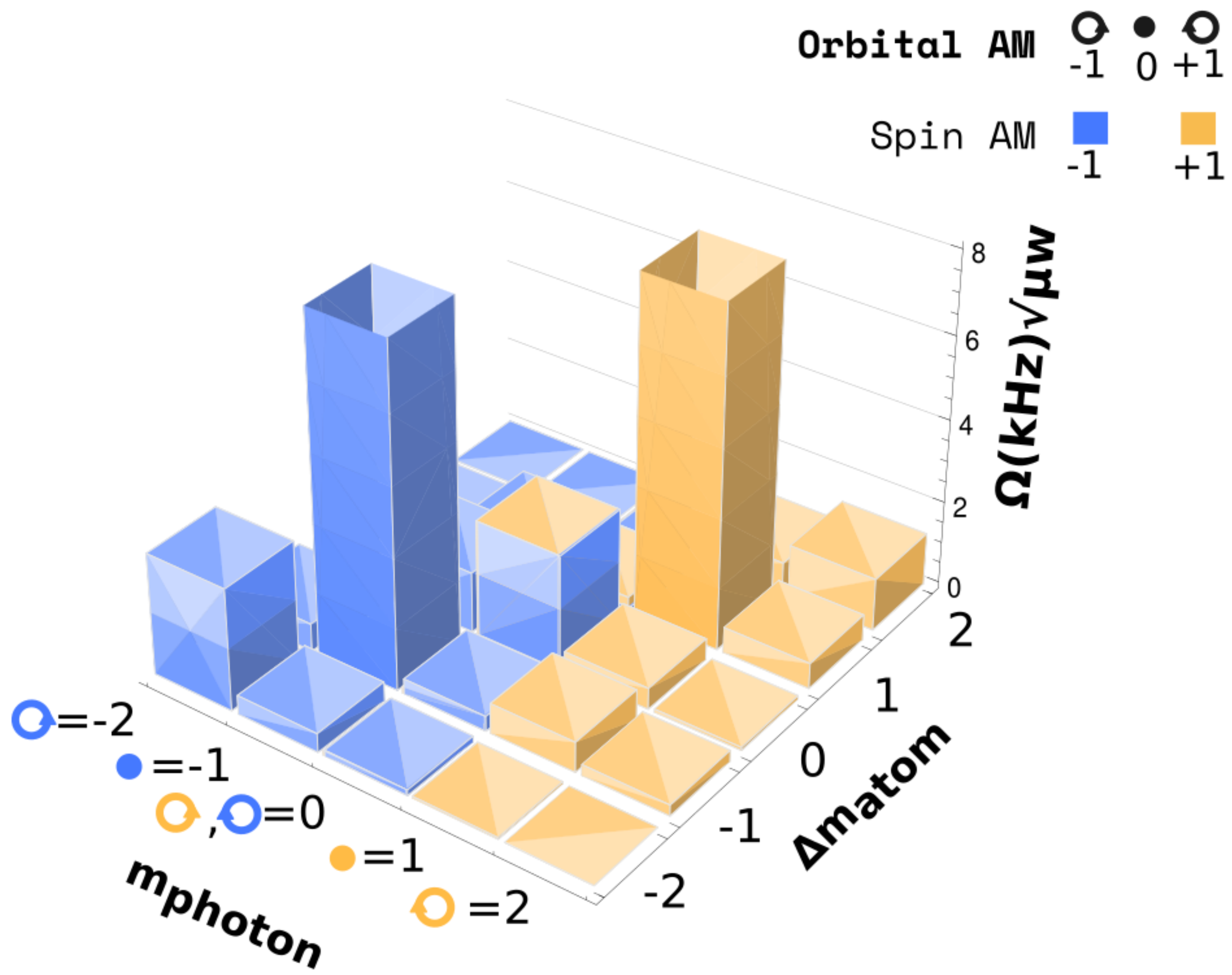
Change in angular momentum of atom

Angular momentum of photon

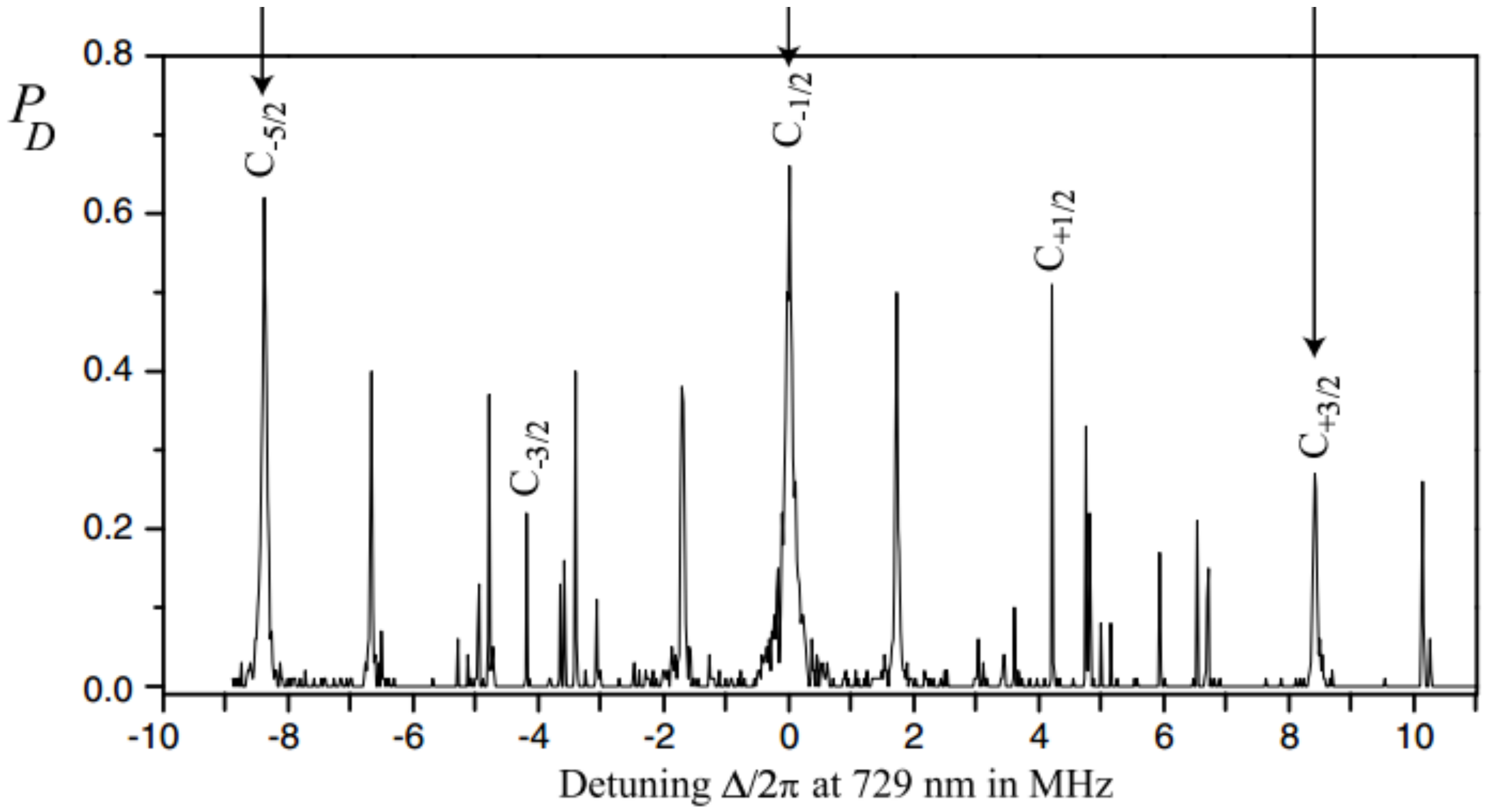
Nature communications 7, 12998 (2016)

Twisting in the dark

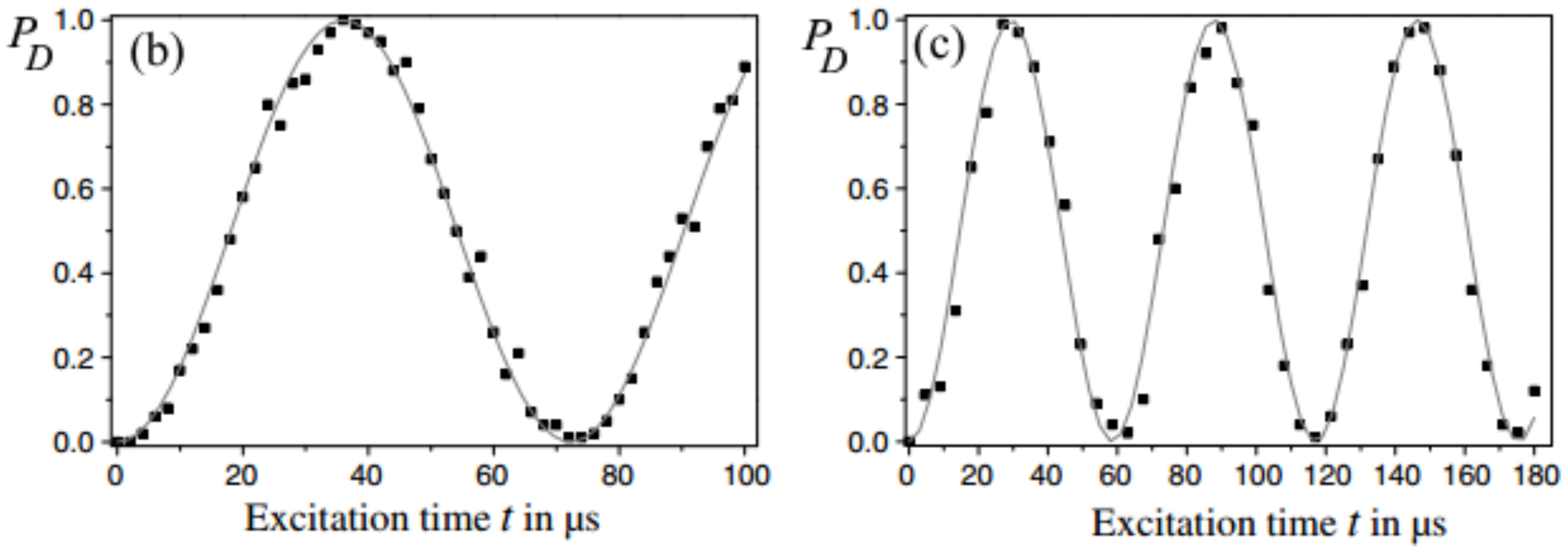
Extra. How we measure.



1) find your peaks for each transition



2) tune to each peak and measure Rabi oscilations



3) repeat for each SAM and OAM configuration

Spectrum example and Rabi oscillation
taken from Gulde Phd (2003)

Light-Matter Interaction - a summary

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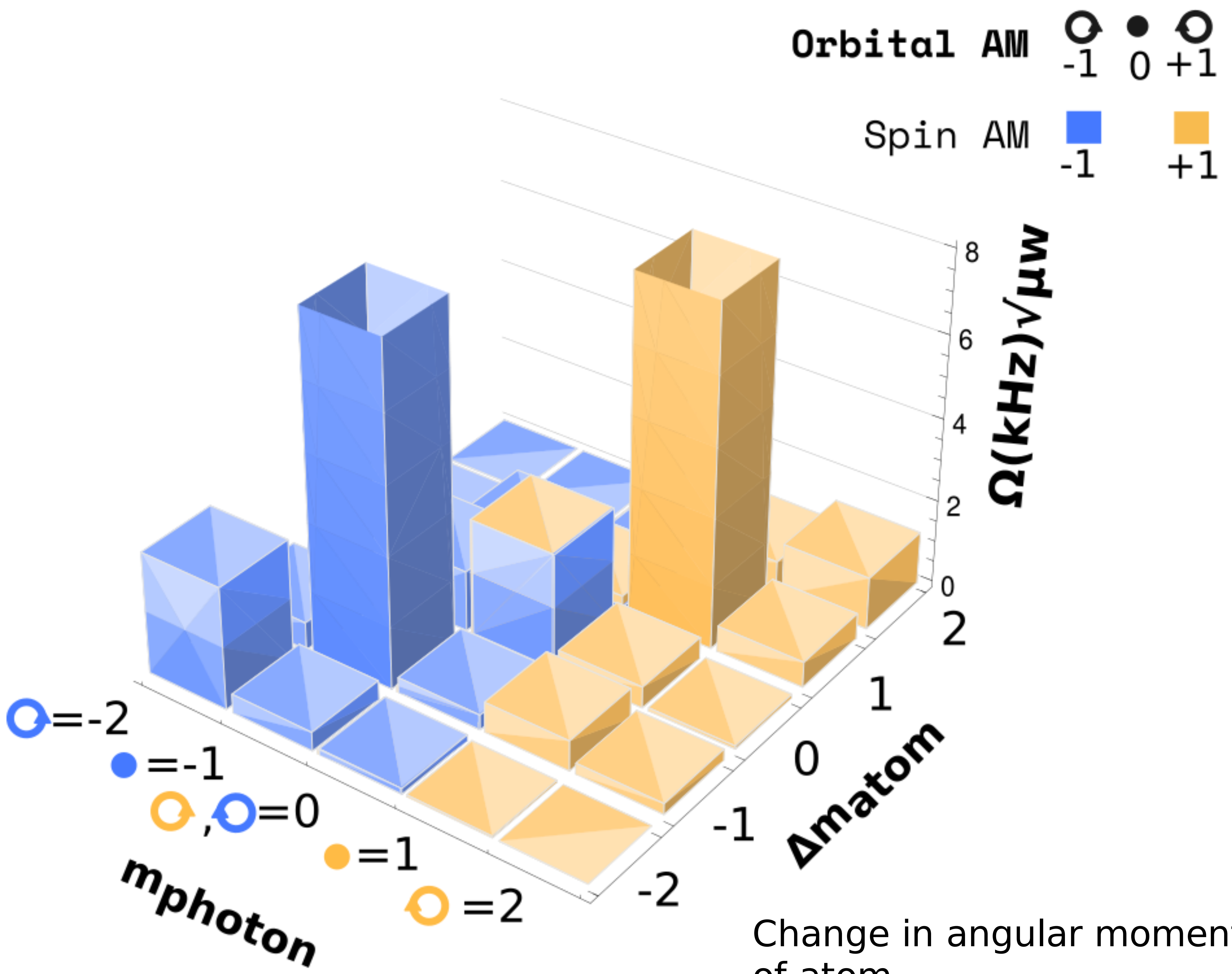
Spin Angular Momentum	✓ Hanle & Bät	✓ Beth	✓ Optical Activity
Orbital Angular Momentum	✓ We!!	✓ Rubenstein Dunlop	

Twisting in the dark - cuantitative results.

Rabi frequencies for each transition

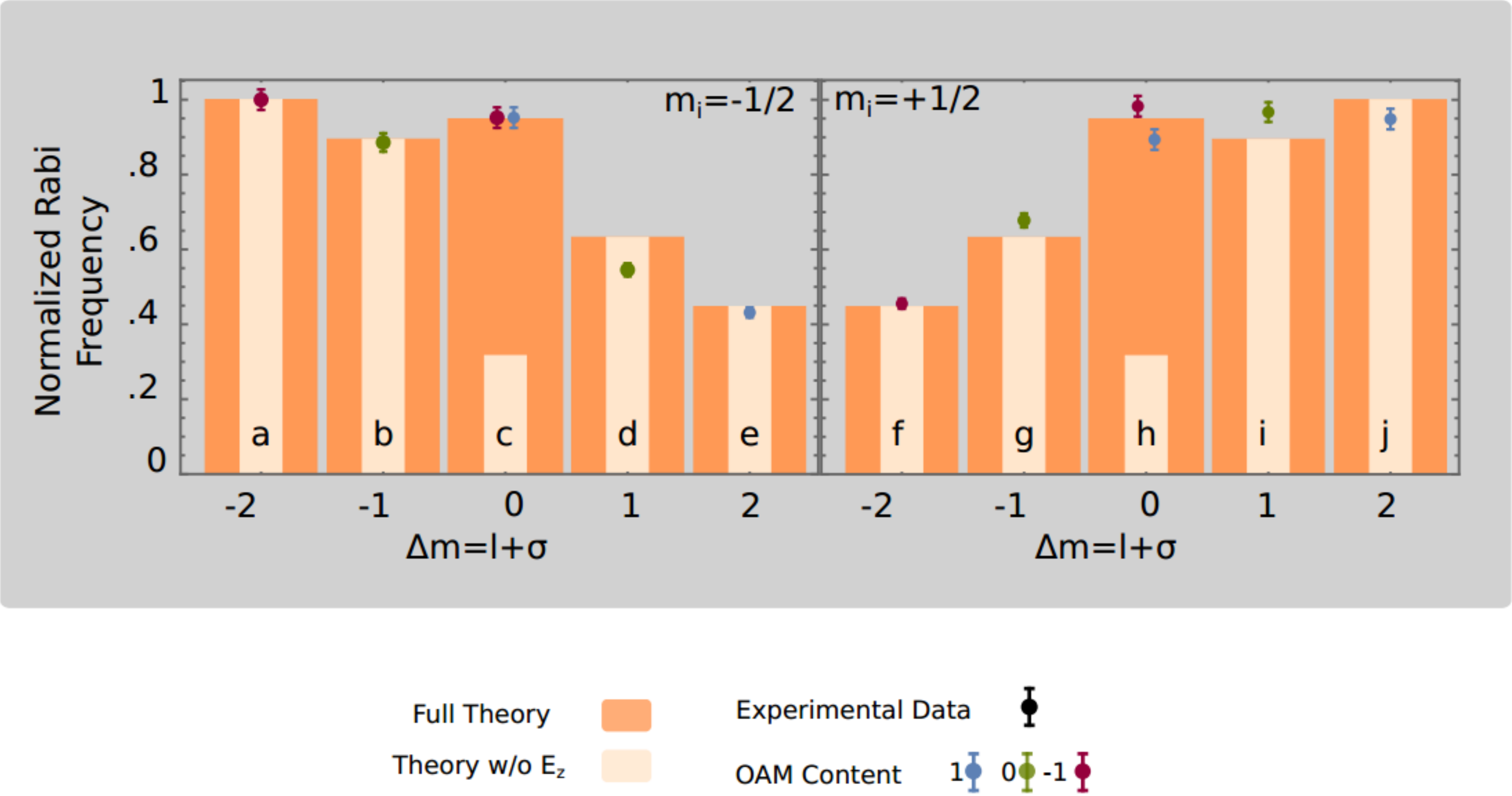


Change in angular momentum of atom

Angular momentum of photon

Nature communications 7, 12998 (2016)

Selection Rules account for Orbital Angular Momentum

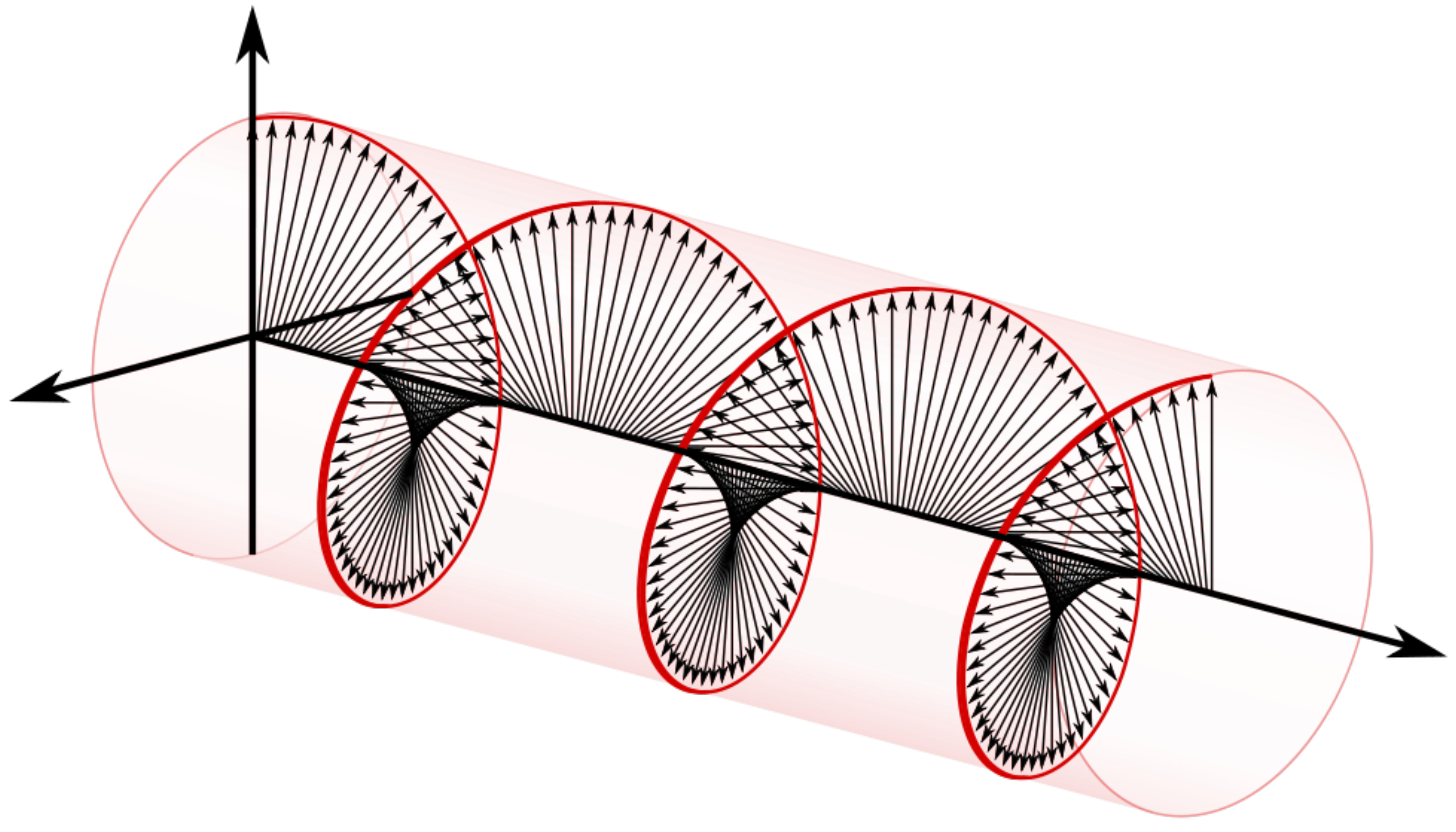


Quinteiro, Schmidt-Kaler, Schmiegelow PRL 119, 253203 (2017)

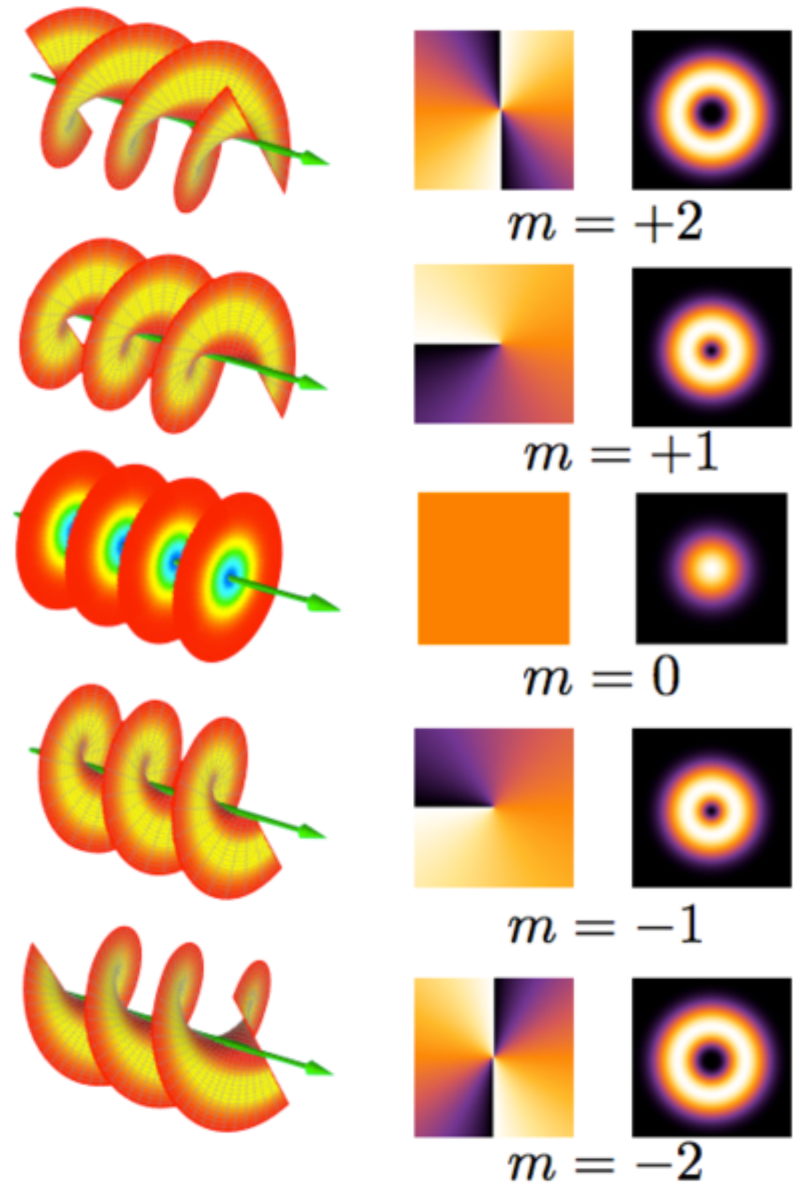
Stong Focusing of Beams - beyond the paraxial approximation

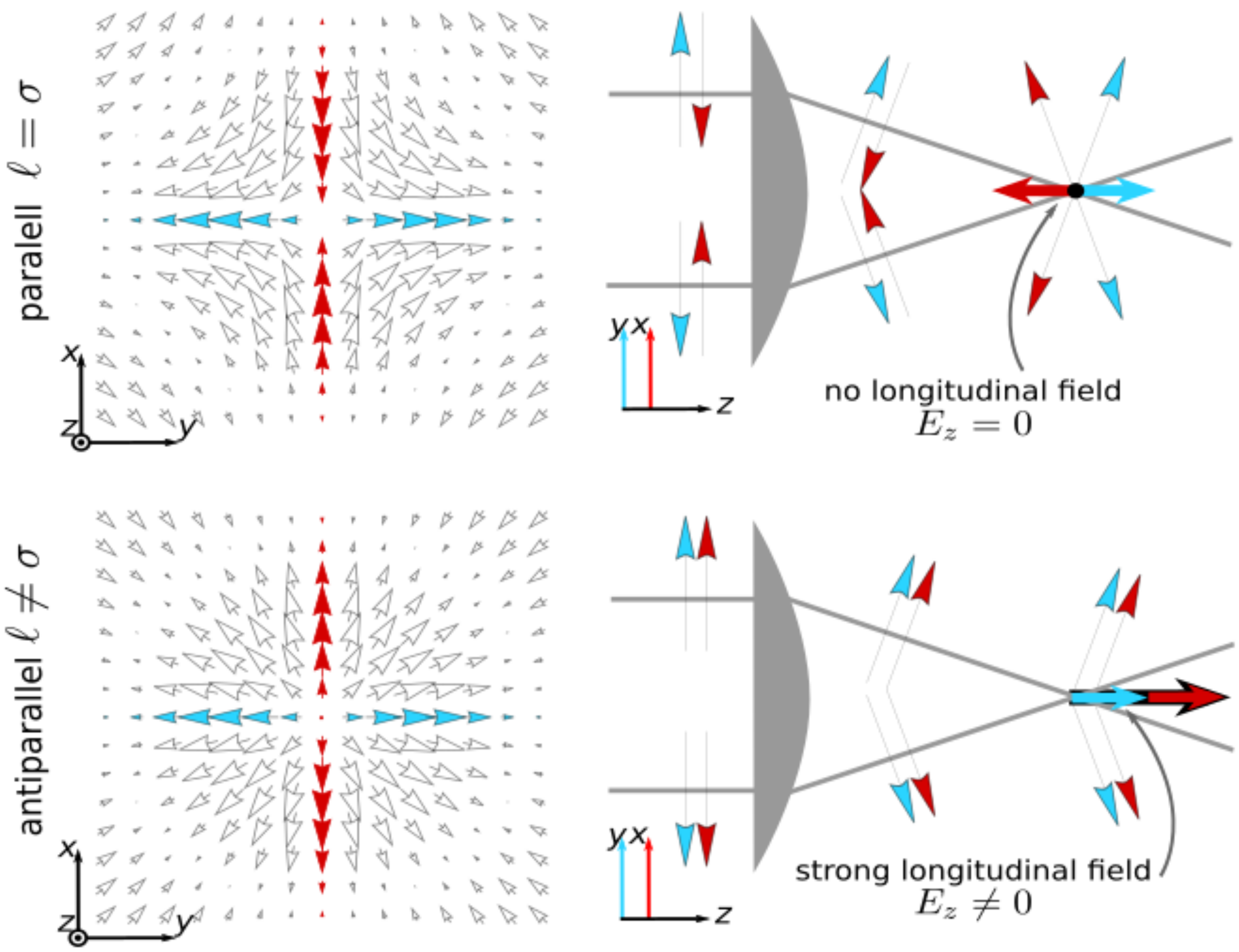
Focusing of LG beams with circular polarization

spin/polarization $\sigma = \pm 1$



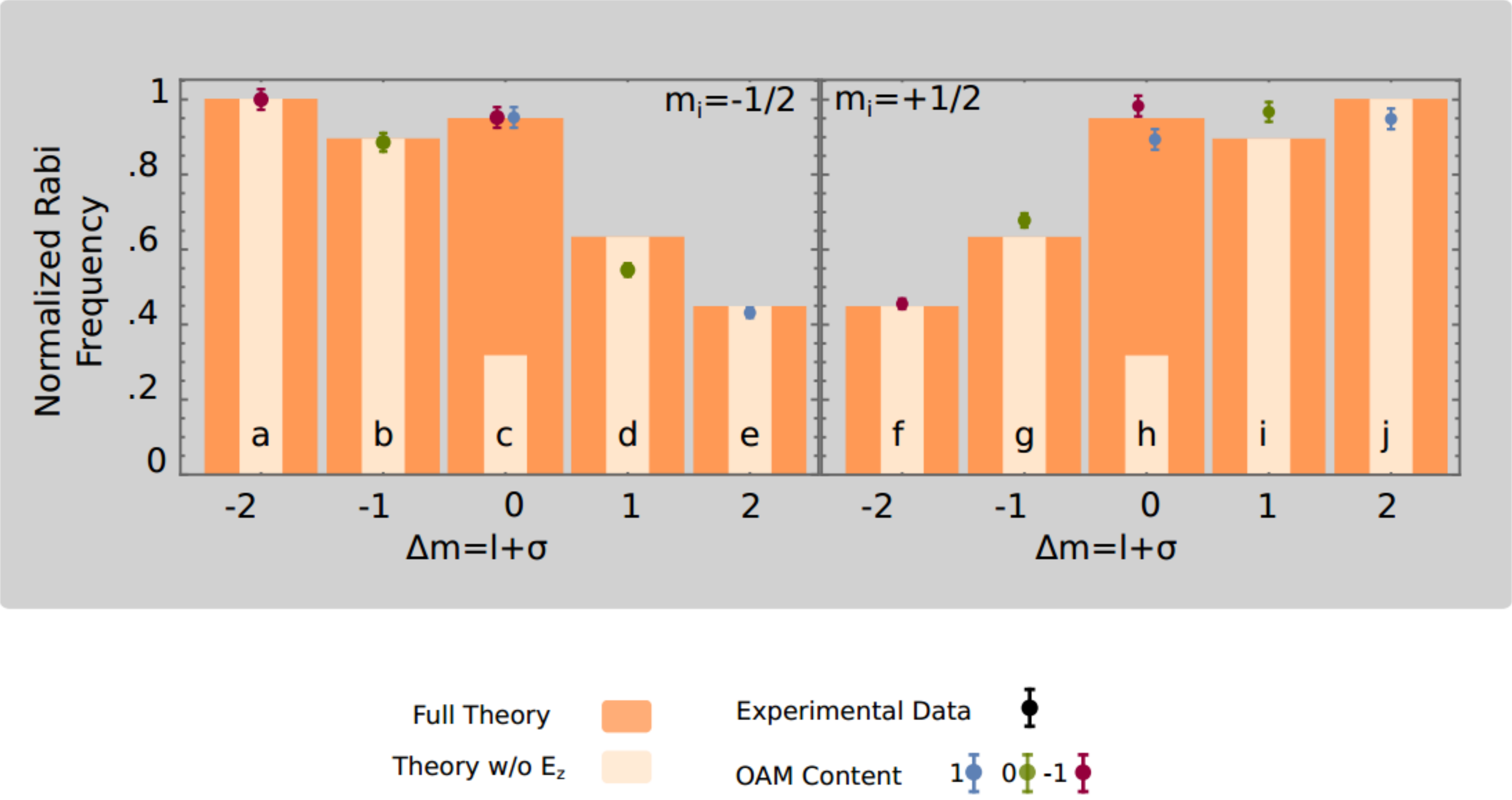
orbital/structure $\ell = 0, \pm 1, \pm 2, \cdots$





Christian Schmiegelow - Universidad de Buenos Aires

Selection Rules account for Orbital Angular Momentum



Quinteiro, Schmidt-Kaler, Schmiegelow PRL 119, 253203 (2017)

Day Two

Part 5

Optical Activity

Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
Energy - Linear Momentum	✓ Fraunhofer	✓ Radiation Pressure	✓ Refraction
Spin Angular Momentum	✓ Hanle & Bät	✓ Beth	✓ Optical Activity
Orbital Angular Momentum	✓ We!!	✓ Rubenstein Dunlop	?

Araoka, F., Verbiest, T., Clays, K. & Persoons, A. Interactions of twisted light with chiral molecules: an experimental investigation. *Phys. Rev. A* **71**, 055401 (2005).

Löffler, W., Broer, D. J. & Woerdman, J. P. Circular dichroism of cholesteric polymers and the orbital angular momentum of light. *Phys. Rev. A* **83**, 065801 (2011).

Mathevet, R., de Lesegno, B. V., Pruvost, L. & Rikken, G. L. J. A. Negative experimental evidence for magneto-orbital dichroism. *Opt. Express* **21**, 3941–3945 (2013).

Light-Matter Interaction - optical actvity

OPTICS

Resolving enantiomers using the optical angular momentum of twisted light

Ward Brullot, Maarten K. Vanbel, Tom Swusten, Thierry Verbiest*

Division Molecular Imaging and Photonics, Department of Chemistry, KU Leuven (University of Leuven), Celestijnenlaan 200D, Box 2425, 3001 Leuven, Belgium.
*Corresponding author. E-mail: thierry.verbiest@fys.kuleuven.be

2016

Circular dichroism and optical rotation are crucial for the characterization of chiral molecules and are of importance to the study of pharmaceutical drugs, proteins, DNA, and many others. These techniques are based on the different interactions of enantiomers with circularly polarized components of plane wave light that carries spin angular momentum (SAM). For light carrying orbital angular momentum (OAM), for example, twisted or helical light, the consensus is that it cannot engage with the chirality of a molecular system as previous studies failed to demonstrate an interaction between optical OAM and chiral molecules. Using unique nanoparticle aggregates, we prove that optical OAM can engage with materials' chirality and discriminate between enantiomers. Further, theoretical results show that compared to circular dichroism, mainly based on magnetic dipole contributions, the OAM analog helical dichroism (HD) is critically dependent on fundamentally different chiral electric quadrupole contributions. Our work opens new venues to study chirality and can find application in sensing and chiral spectroscopy.

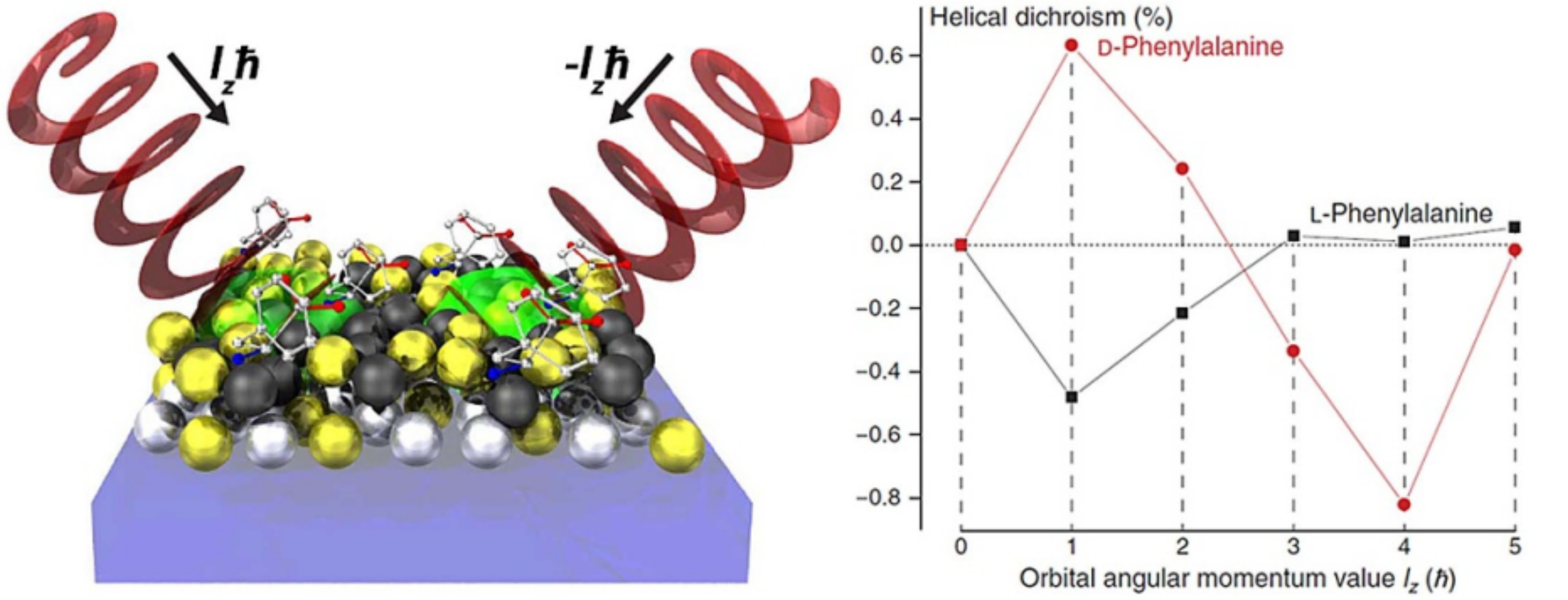


Figure 8. Left: In this schematic (not-to-scale), the right- and left-handed LG beams (red) interact differently (green shade) with chiral molecules (stick-and-ball models) adsorbed to the nanoparticle aggregates. Right: VD measurements as a function of OAM value, exhibiting the difference in transmission for right- and left-handed vortex light with clear discrimination between molecular enantiomers. Reproduced from [80] (CC BY 4.0), where what we term vortex dichroism is called helical dichroism.

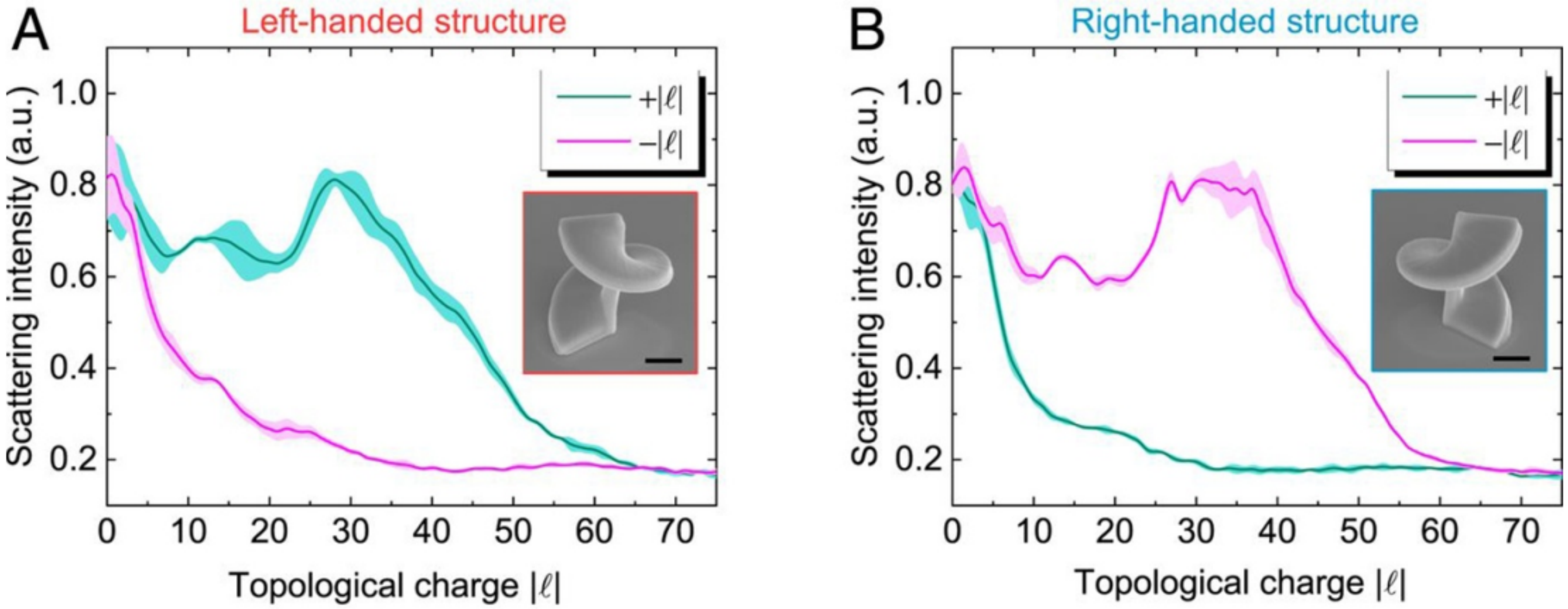
Light-Matter Interaction - optical actvity

Gigantic vortical differential scattering as a monochromatic probe for multiscale chiral structures

Jincheng Ni[a,b], Shunli Liu[a], Dong Wu[a,1], Zhaoxin Lao[a], Zhongyu Wang[a], Kun Huang[c,1], Shengyun Ji[a], Jiawen Li[a], Zhixiang Huang[d], Qihua Xiong[e], Yanlei Hu[a,1], Jiaru Chu[a], and Cheng-Wei Qiu[b,1]

[a]Chinese Academy of Sciences Key Laboratory of Mechanical Behavior and Design of Materials, Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, 230027 Hefei, China; [b]Department of Electrical and Computer Engineering, National University of Singapore, 117583 Singapore, Singapore; [c]Department of Optical Engineering, University of Science and Technology of China, 230026 Hefei, China; [d]Key Laboratory of Intelligent Computing and Signal Processing (Ministry of Education), Anhui University, 230039 Hefei, China; and [e]Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 637371 Singapore, Singapore

2020



Light-Matter Interaction - optical actvity

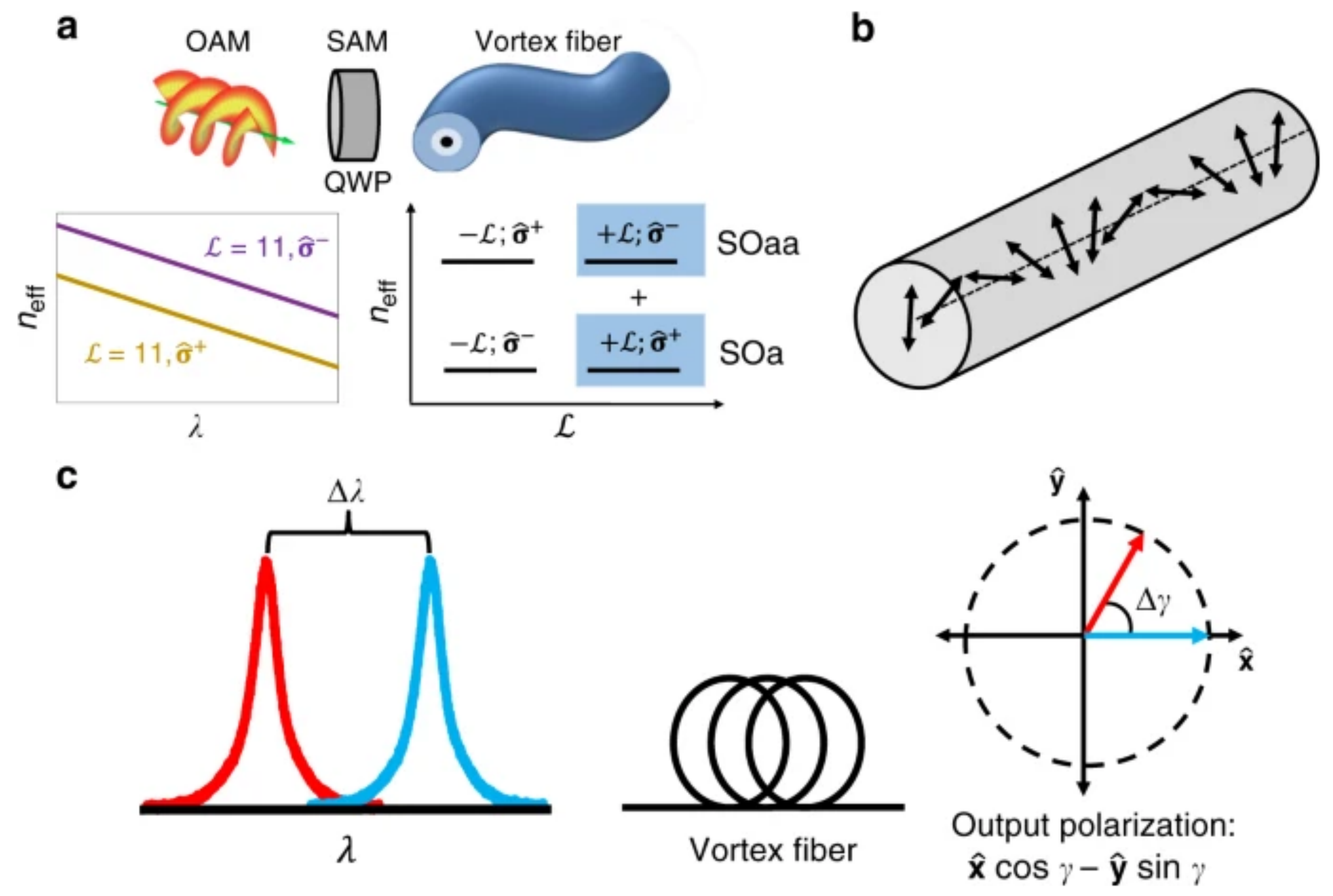
Article | Open access | Published: 16 October 2020

High resolution spectral metrology leveraging topologically enhanced optical activity in fibers

Aaron P. Greenberg, Gautam Prabhakar & Siddharth Ramachandran

Nature Communications 11, Article number: 5257 (2020) | Cite this article

Fig. 1: Vortex fiber superposition phenomena.



OAM sorting though SOAM OAm coupling in "vortex" fibers.

BUT WAIT!

Then any AOM mode sorter is an optically active material.

See review:

Orbital angular momentum of twisted light: chirality and optical activity
Kayn A Forbes and David L Andrews 2021 J. Phys. Photonics 3 022007

Light-Matter Interaction - a summary

	Atomic Spectroscopy	Mechanical Effects on Matter	Mechanical Effects on Light
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Light-Matter Interaction - a summary

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Tomorrow

Day Two

Part 4

AC Stark Shifts

AC Stark Shift, Autler-Townes effect hamiltonian and time evolution

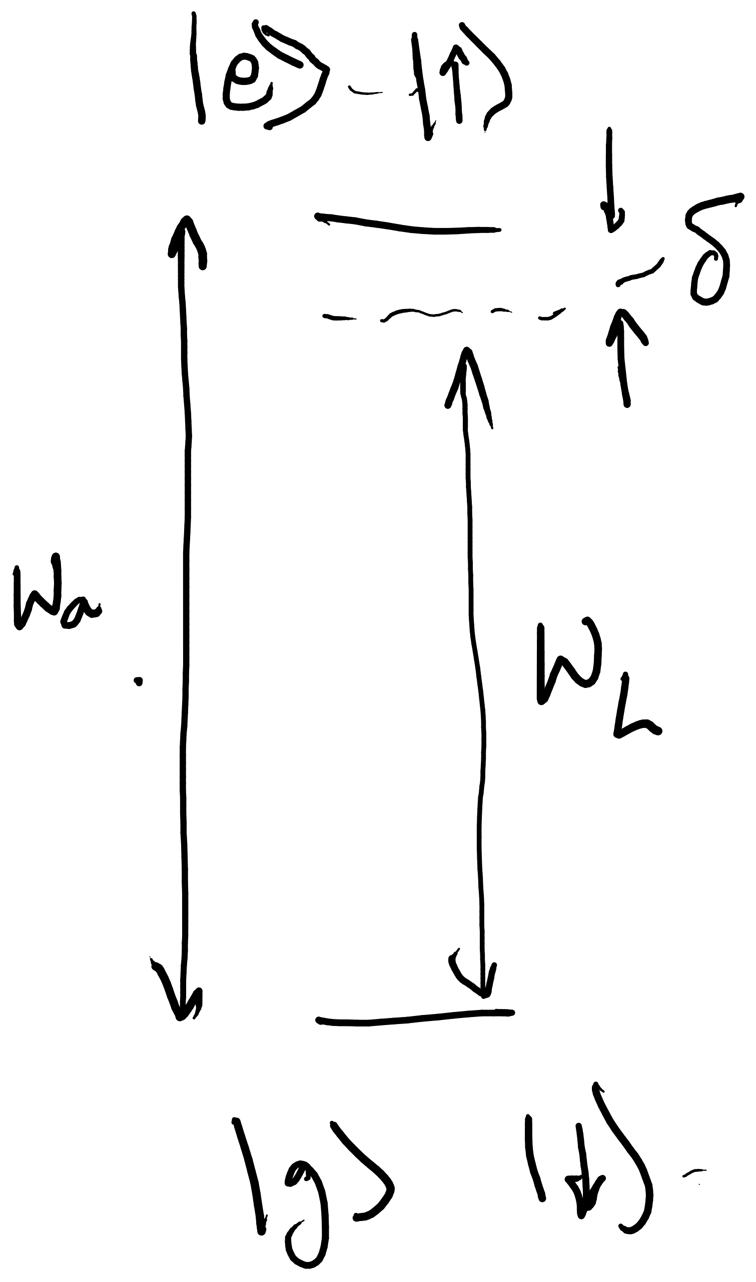
Hamiltonian

$$H = H_0 + H_{\text{int}}$$

$$H_0 = \sigma_z \frac{\hbar\omega_a}{2}$$

$$= \frac{\hbar\omega_a}{2}|e\rangle\langle e| - \frac{\hbar\omega_a}{2}|g\rangle\langle g|$$

$$H_{\text{int}} = \hbar\Omega\,\sigma_x \cos(\omega_l t)$$



Going to a frame rotating as...

$$U = \exp\{-i\sigma_z(\omega_l - \delta)t/2\}$$

The hamiltonian, tranforms, in the rotating wave approximation to:

$$H' \approx \frac{\hbar\delta}{2}\sigma_z + \hbar\Omega\,\sigma_x$$

$$H' \approx \hbar\Omega' \left(\frac{\delta}{2\Omega'}\sigma_z + \frac{\Omega}{\Omega'}\sigma_x\right)$$ where $\Omega' = \sqrt{\Omega^2 + \delta^2/4}$

when $\delta \gg \Omega$

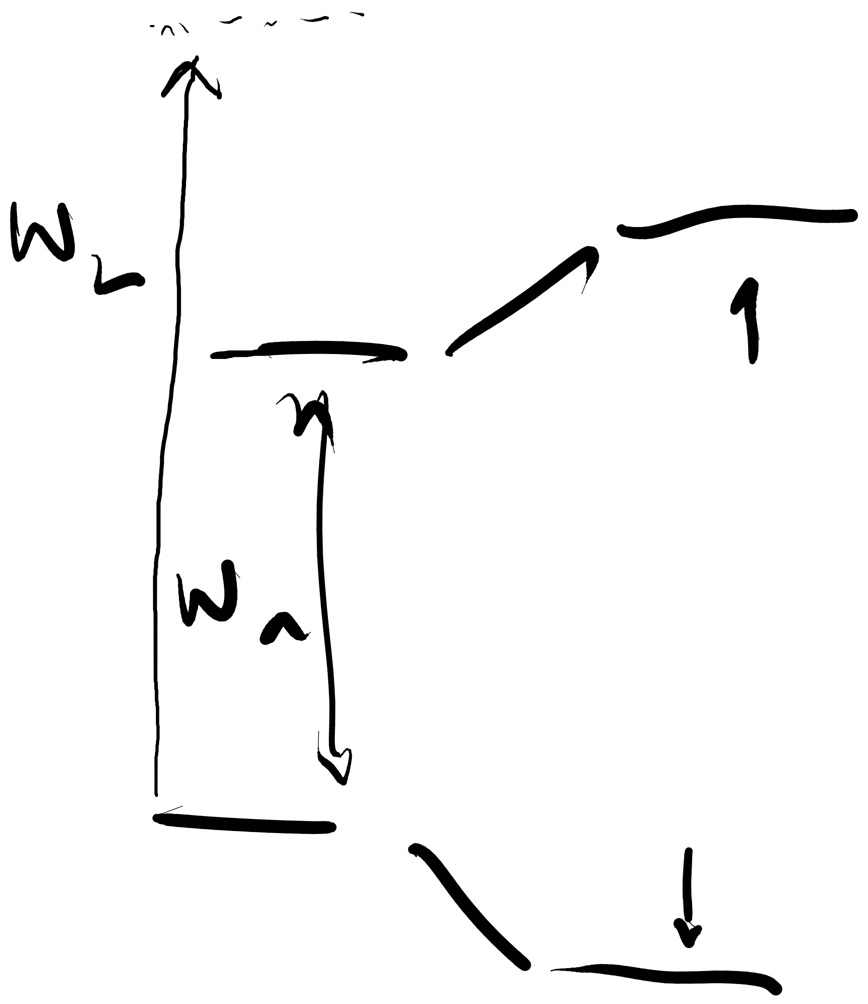
$$H' \approx \hbar\Omega' \left(\frac{\delta}{2\Omega'}\sigma_z + \frac{\Omega}{\Omega'}\sigma_x\right)$$

1 0

$$\Omega' \to \frac{\delta^2}{2} + \frac{\Omega^2}{\delta}$$

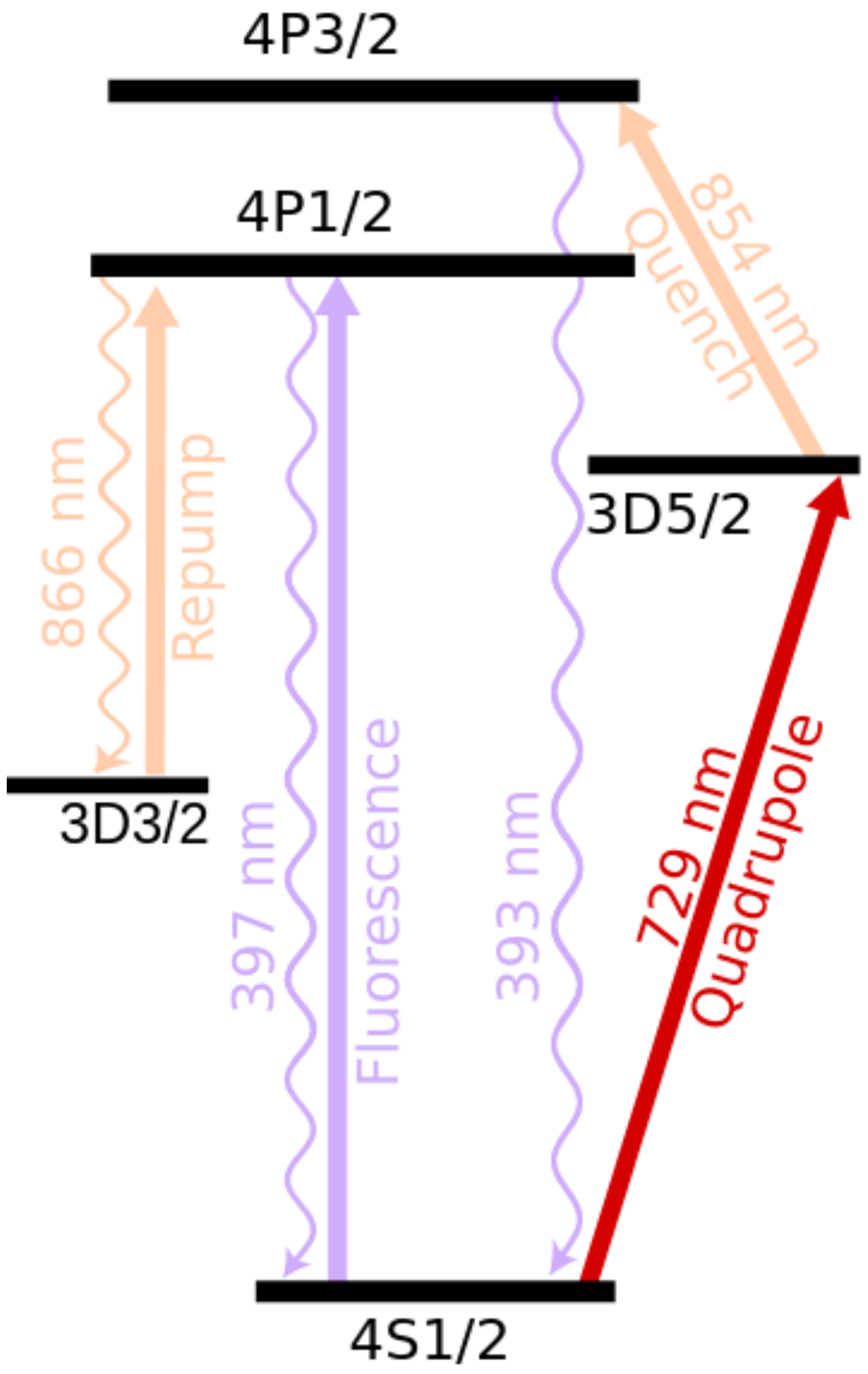
Trasnforming back

$$H = \sigma_z \left(\frac{\hbar\omega_a}{2} + \frac{\Omega^2}{\delta}\right)$$



AC Stark Shift problems and applications

Problems for frequency standars



We demostrated a reduction in the AC stark shif of ~40x

AC Stark Shift problems and applications

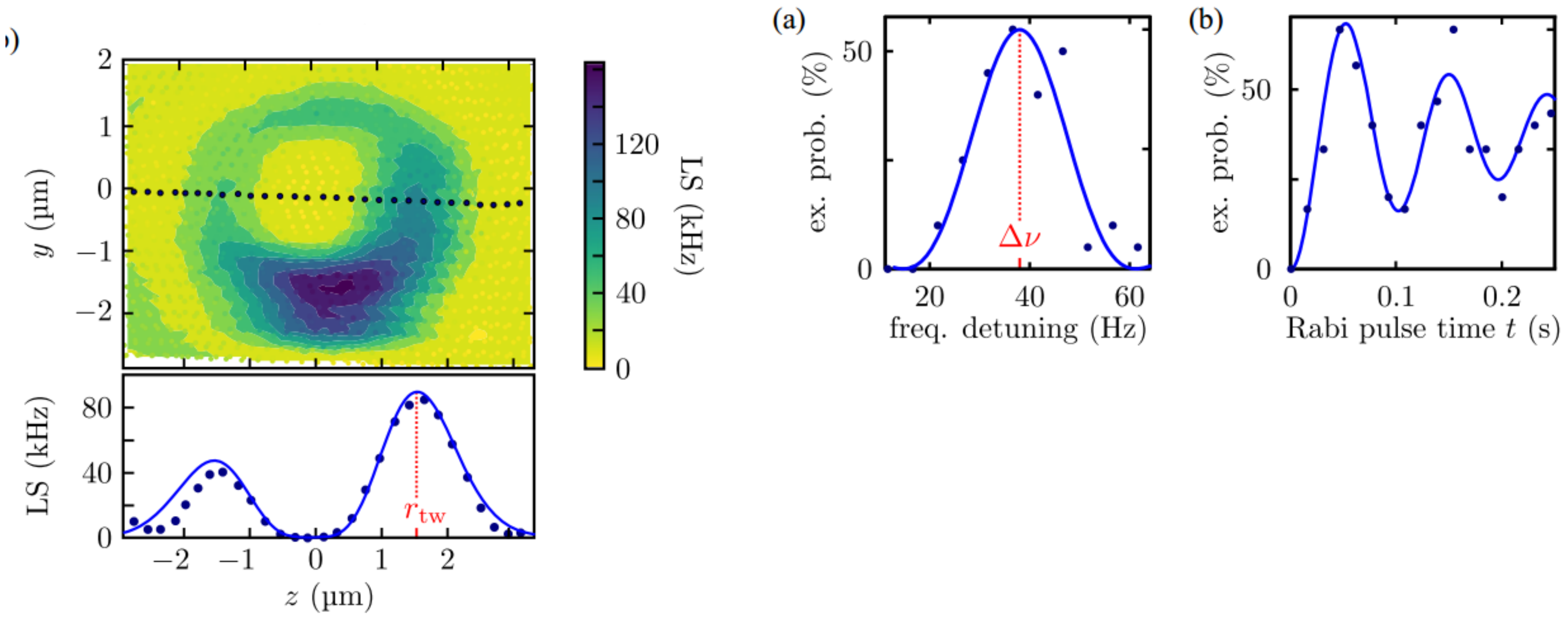
Problems for frequency standars

PHYSICAL REVIEW LETTERS **129**, 253901 (2022)

Excitation of an Electric Octupole Transition by Twisted Light

R. Lange,[1] N. Huntemann,[1,*] A. A. Peshkov,[1,2] A. Surzhykov,[1,2,3] and E. Peik[1]
[1]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2]*Institut für Mathematische Physik, Technische Universität Braunschweig, Mendelssohnstraße 3, 38106 Braunschweig, Germany*
[3]*Laboratory for Emerging Nanometrology, Langer Kamp 6a/b, 38106 Braunschweig, Germany*

(Received 20 June 2022; accepted 14 November 2022; published 12 December 2022)



$$\xi = \Omega^2/\Delta\nu$$

$$\xi_{tw} = 135(5)\ \text{Hz}$$
$$\xi_{pl} = 30.3(9)\ \text{Hz}$$

$$\xi_{tw}/\xi_{pl} = 4.5(2).$$

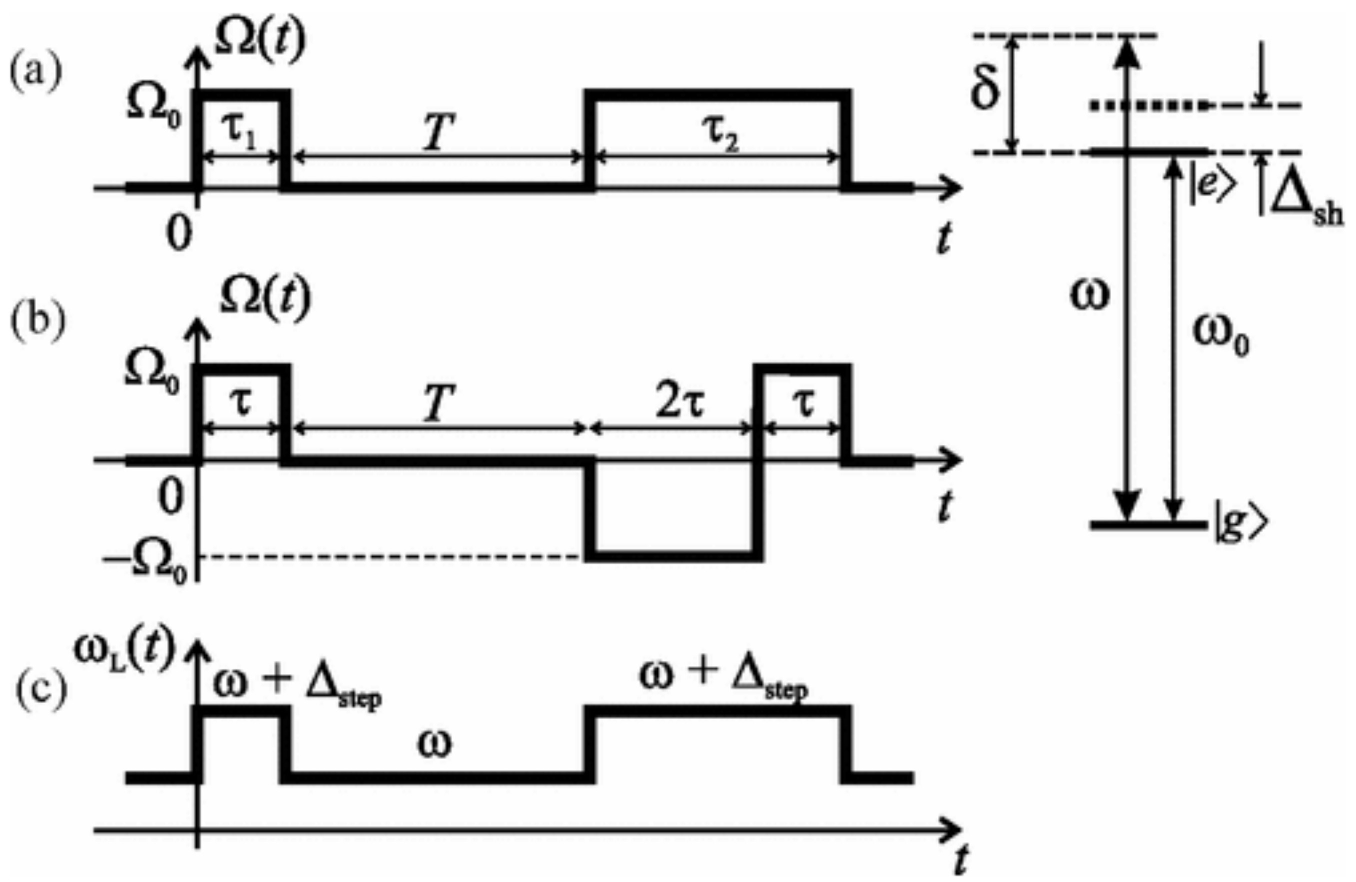
AC Stark Shift problems and applications

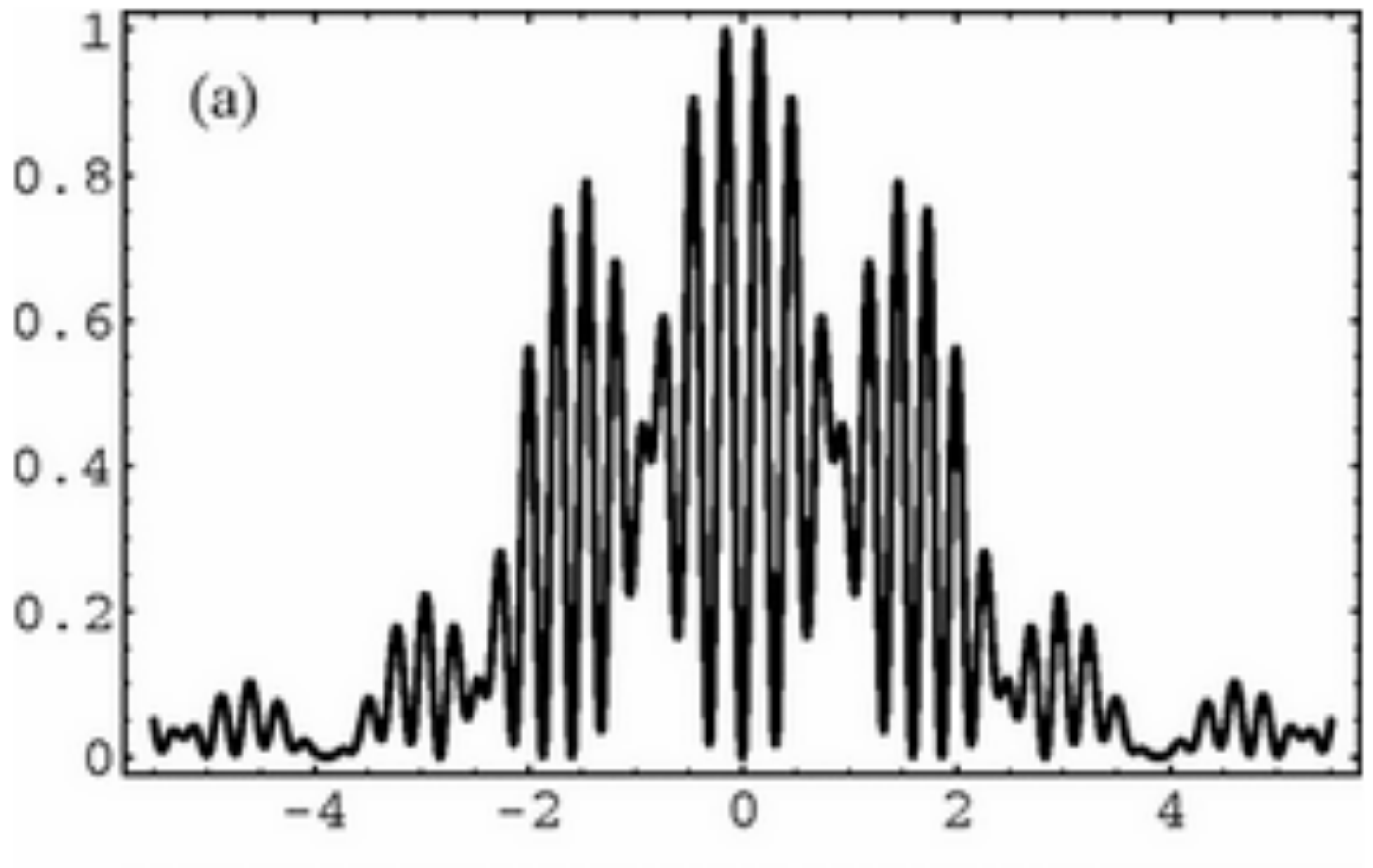
Problems for frequency standars

The devil's advocate: hyper-Ramsey and balanced-Ramsey spectrocopy

PHYSICAL REVIEW A **82**, 011804(R) (2010)

Hyper-Ramsey spectroscopy of optical clock transitions



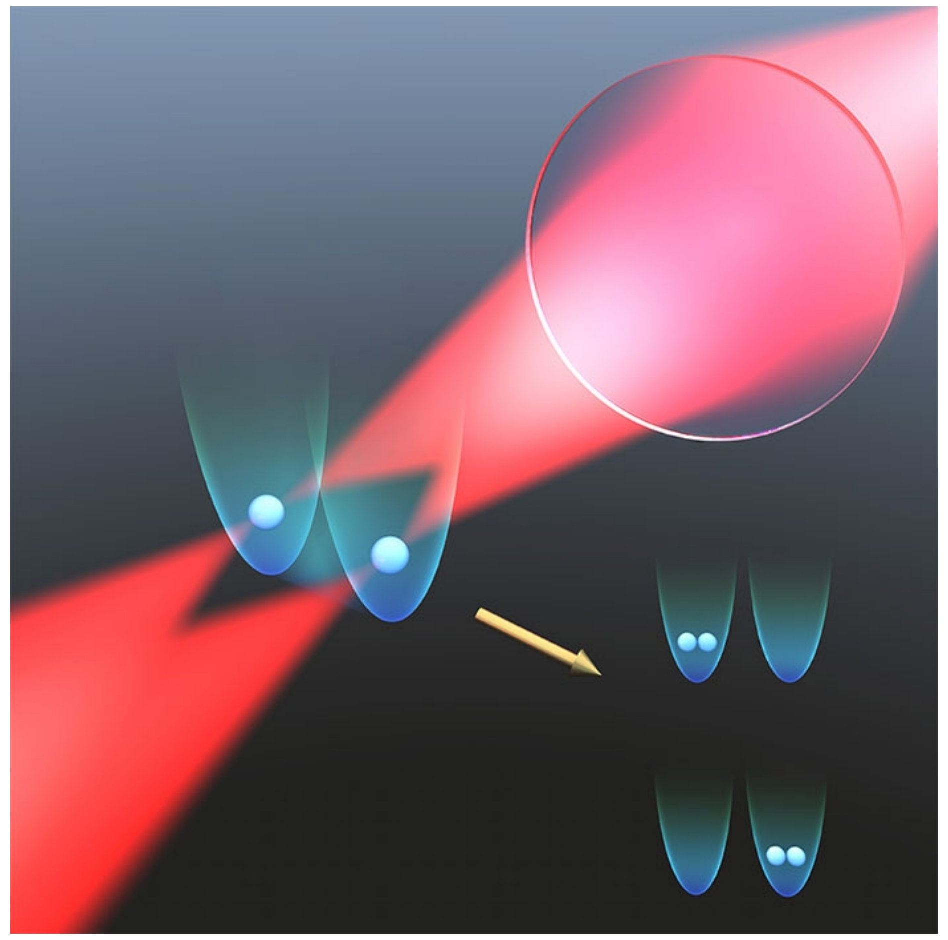


Suppression of AC stark Shift by 2-4 orders of magnitude

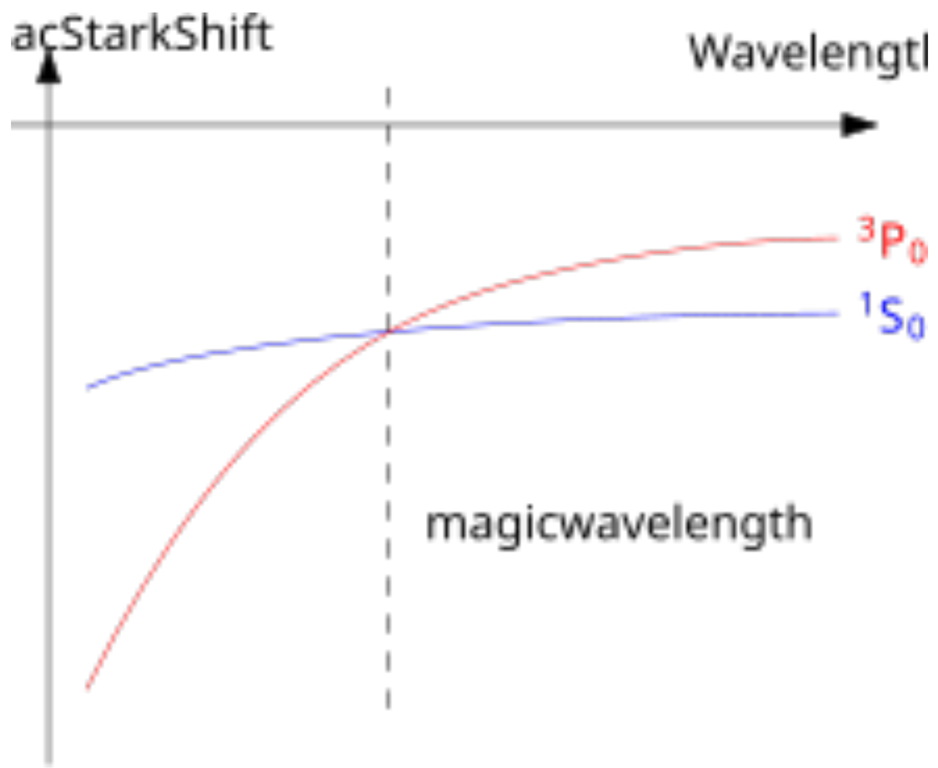
AC Stark Shift problems and applications

Optical Tweezers and Magic Wavelength

Low and high field seakers $\delta > 0$ or $\delta < 0$

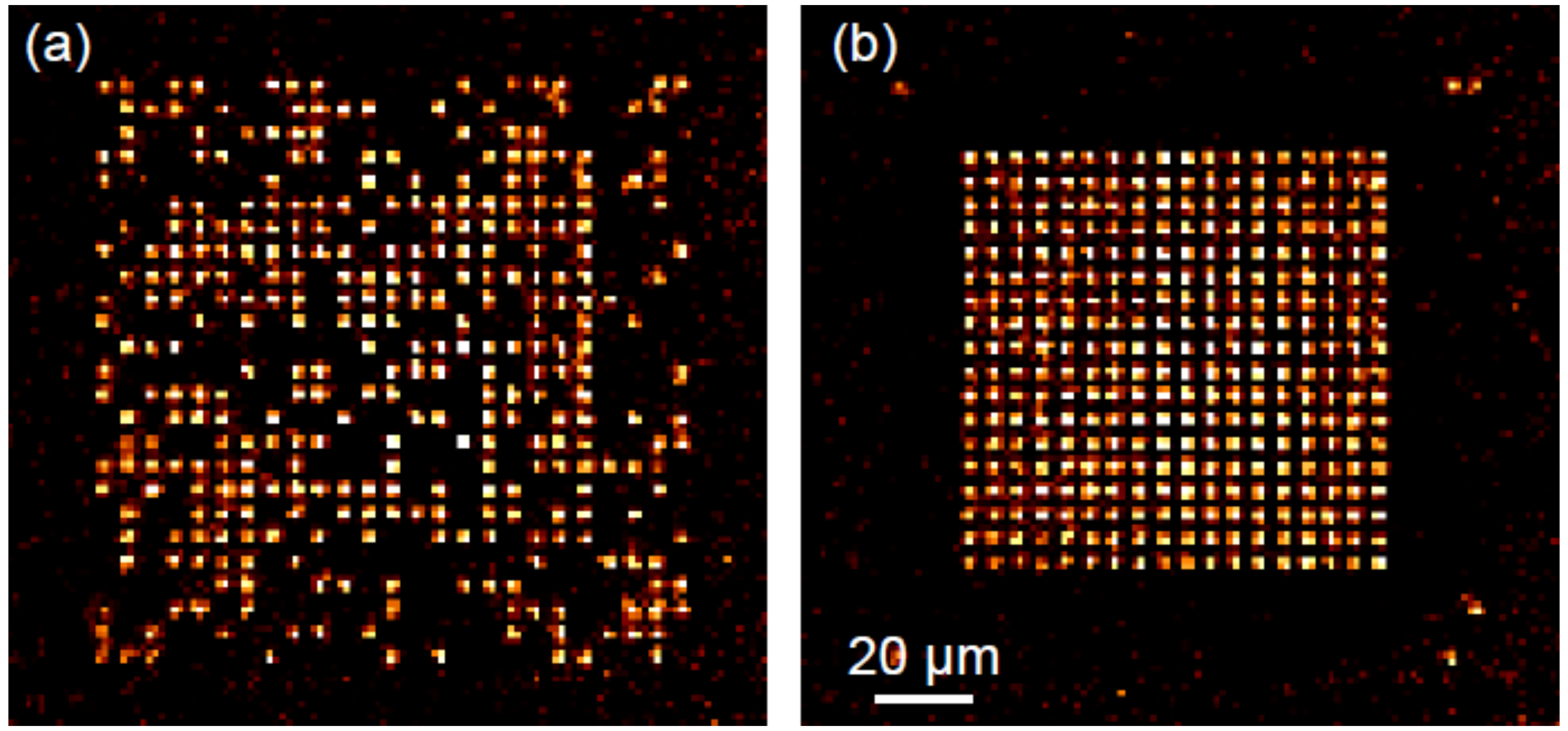


Magic Wavelength



Allows optical trapping,
leaving one (clock or qubit) transition undisturbed.

Atom arrays (record Quantum Volume by Lukin Group)



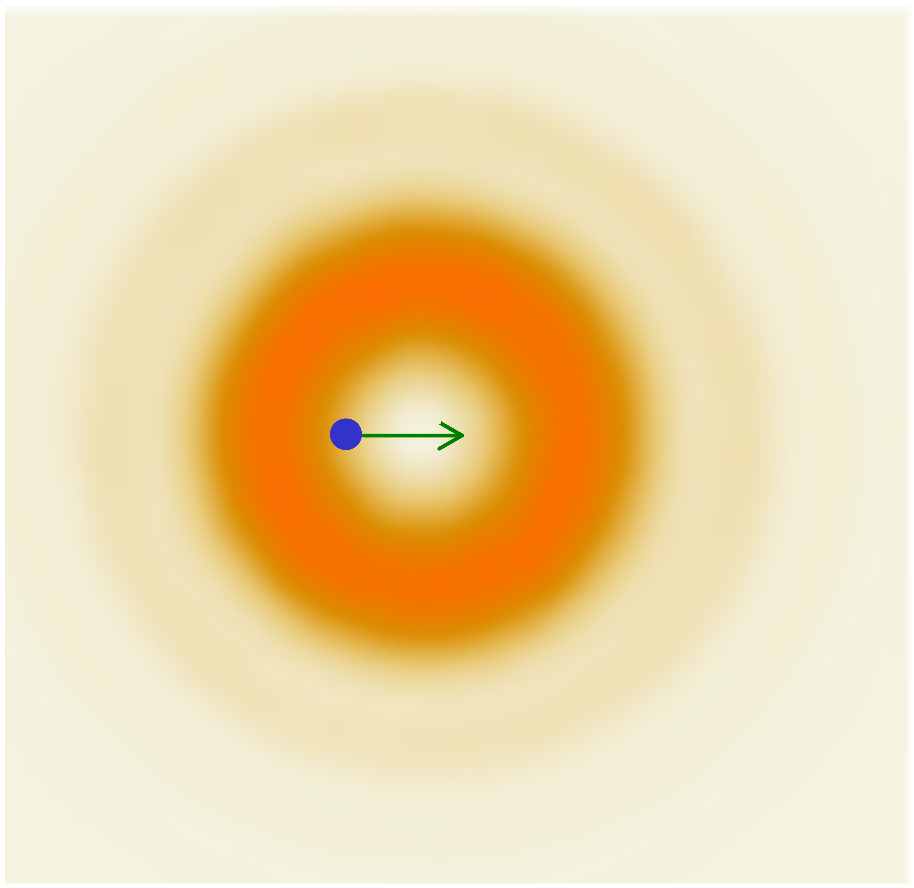
cred. Inst. d' Optique, Paris

AC Stark Shift problems and applications

Spin dependent forces.

Standing Waves

Structured Beams



Existing Applications

Gates betweeen ions.
Generation of cat states.
Generation of sweezed states.
Sping dpenedent motional control of ions and atoms.

Proposed Applications

Same, but without problems of phase stability!

Thank you for you attention.